Tensor imaging and tractography are diffusion-based MR techniques for advanced functional imaging of brain white matter. Imaging brain anisotropy can yield useful information about white matter (WMI) integrity and demonstrate pathology occult to conventional imaging techniques. Anisotropy imaging can also provide information about ordered white matter tracts such as directional orientation and connectivity, which can be useful in the understanding of certain developmental and acquired disease states.

With appropriately applied magnetic field gradients, MR images can be sensitized to diffusion, or the random thermally driven motion of water molecules in tissue. Water movement is essentially random in brain gray matter, but diffusion is anisotropic, or directionally oriented, in WM tracts. There, axonal membranes and myelin sheaths present barriers to water motion in directions other than parallel to fiber orientation. The direction of maximum diffusivity coincides with WM fiber tract orientation.

This information is contained in the diffusion tensor, a mathematical model of diffusion in 3D space. The tensor is a matrix of numbers derived from diffusion measurements in at least six different directions from which diffusivity in any direction can be estimated and the direction of maximum diffusivity can be determined.

The tensor matrix can be visualized as an ellipsoid. The diameter in any direction estimates the diffusivity in that direction, and the major principal axis is oriented in the direction of maximum diffusivity. The degree to which the diffusion tensor shape differs from that of a sphere (random motion) represents anisotropy (ordered motion).

With diffusion tensor imaging (DTI), the degree of anisotropy as well as local fiber orientation can be mapped, providing an opportunity to study WM architecture and evaluate fiber integrity.

WM fiber tracts are classified as association, projection, or commissural fibers (Table 1). Association fibers connect cortical areas in each hemisphere. Projection fibers connect cortical areas with deep nuclei, brain stem, cerebellum, and spinal cord. Commissural fibers connect similar cortical areas between opposite hemispheres. Three-D tract rendering is accomplished with commercially available

### Table 1. Fiber Types and Locations

<table>
<thead>
<tr>
<th>Association Fibers</th>
<th>Projection Fibers</th>
<th>Commissural Fibers</th>
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<tbody>
<tr>
<td>Cingulum</td>
<td>Corticospinal tracts</td>
<td>Corpus callosum</td>
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<tr>
<td>Superior occipitofrontal fasciculus</td>
<td>Coricobulbar tracts</td>
<td>Anterior commissure</td>
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<tr>
<td>Inferior occipitofrontal fasciculus</td>
<td>Corticopontine tracts</td>
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<td>Uncinate fasciculus</td>
<td>Geniculocalcarine tracts (optic radiations)</td>
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<tr>
<td>Superior longitudinal (arcuate) fasciculus</td>
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<tr>
<td>Inferior longitudinal (occipitotemporal) fasciculus</td>
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software that can be found on the scanner or workstation. While individual tract parsing is imperfect, in some circumstances incompletely extracting individual tracts, these techniques are still quite efficacious at display and evaluation of the ordered WM.

Clinical Utility

DTI has also been used to investigate brain development and assist in understanding the organization of the brain white matter in developmental brain abnormalities, often demonstrating additional findings beyond those seen with conventional MR imaging (Figure 1).

The preservation of vital cerebral function while maximizing lesion resection is the principal goal in brain neurosurgery. Cortical mapping can be accomplished intraoperatively with electrocortical stimulation. Preoperatively, functional MR techniques such as blood oxygen level-dependent (BOLD) imaging are used in the localization of eloquent cerebral cortex. Neither cortical mapping nor BOLD imaging provides information about WM tracts in or adjacent to brain lesions, however. Two-D and 3D WM tractography techniques can be very powerful in elucidating relationships of deep brain lesions to eloquent brain structures.

White matter imaging is used to estimate the relationship of the lesion to tracts responsible for brain activity such as motor function (corticospinal tracts). DT tractography, which requires five to seven minutes to scan and is easily processed with commercially available software, is practical and easily integrated into the armamentarium of techniques of the high-end neurologically oriented clinical practice, as shown in the following examples.

Case study one. A 13-year-old girl, diagnosed at an outside institution with a low-grade thalamic glioma, was referred to the New Jersey Neuroscience Institute for evaluation for resection. As a critical part of the planning process, surgeons requested a 3T MR study for detailed anatomic delineation and functional localization. Imaging revealed a well-circumscribed, nonenhancing left thalamic mass distorting local anatomy and obscuring relationships with the adjacent internal capsule. Definitive localization of the blue corticospinal fibers coursing in a cephalocaudal direction was made possible by the directionally encoded 2D tensor images (Figures 2 and 3). These images, along with 3D tractograms seeded and grown from the ipsilateral precentral gyrus WM, showed that the lesion displaced the posterior limb of the internal capsule laterally and inferiorly. The anterior limb of the internal capsule, coded in green as its fibers course anteroposteriorly, was displaced anteromedially. Armed with this functional information, the surgeon resected from a medial approach. After several days, the patient was discharged with no motor deficit after resection.
Case study two. A 35-year-old woman with seizures presented with an outside institution MR study showing a left temporal lobe hemorrhage and other findings suspicious for the presence of an arteriovenous malformation. The patient was referred to Edison Imaging for definitive 3T MR evaluation of the presence of an AVM as well as estimation of the functional significance of lesion resection. Time-resolved contrast-enhanced MRA confirmed the presence of an AVM within the left temporal lobe. Functional MR with BOLD imaging clearly defined the central sulcus and sensorimotor cortex on the surface of the brain but yielded little information related to the surgical approach to the temporal lobe lesion (Figures 4 and 5).

Three-D tractography demonstrated that the lesion and hematoma were separate from the superior longitudinal fasciculus. The optic radiations and inferior longitudinal fasciculi had been destroyed by the lesion, and thus function was not likely to deteriorate further as a result of surgical treatment of the AVM.

Case study three. A 60-year-old patient with a solitary metastatic focus was referred for consideration of resection. Routine anatomic imaging at 3T showed a hypointense metastasis in the vicinity of eloquent cortex. Three-D tractograms obtained by seeding the pre- and postcentral gyri, as determined by BOLD imaging, confirmed the lesion was posterior to the sensory cortex, allowing lesion resection without deficit (Figure 6).

Case study four. A 40-year-old patient with a recurrent high-grade glioma was referred for consideration of lesion debulking. BOLD imaging readily marked the central sulcus, showing that the enhancing portion of the lesion was well posterior to eloquent cortex. Localization of WM fibers with respect to the deeper portions of this large neoplasm was facilitated by 3D tractography. The corticospinal fibers were clearly displaced and bowed anteriorly by the tumor. Lesion debulking did not produce a motor deficit (Figure 7).

Figure 4. Case study 2. Left temporal hemorrhage and flow voids suggest an arteriovenous malformation (left). MRA confirms the presence of a vascular lesion (right).

Figure 5. Case study 2. BOLD study (upper left) identifies central sulcus. 3D tractography (upper right) reveals hemorrhage to be inferior to superior longitudinal fasciculus. Axial TI-weighted image (lower right) and 3D tractogram (lower left) show destruction of portions of the optic radiations and inferior longitudinal fasciculus.

Figure 6. Case study 3. 3D tractograms reveal the hypointense metastatic focus is posterior to sensorimotor white matter tracts.

Figure 7. Case study 4. BOLD study (upper left) suggest tumor infiltration of sensory cortex. Enhancing portion of lesion is inferior and posterior to post-central gyrus (bottom). 3D tractogram (upper right) shows corticospinal tracts displaced anteriorly.
Case study five. A 42-year-old man presented with seizures, and 3T MR imaging revealed a cavernous malformation within the occipital lobe. The goal of neurosurgery was to resect the lesion with minimal disruption of visual function. Tractography demonstrated that the lesion was lateral to the optic radiations and largely inferior and posterior to the inferior longitudinal and inferior occipitofrontal fasciculi, leading to an inferiorly angled superior and posterior approach to lesion removal (Figures 8 and 9).

Clinical Impact

Advanced imaging tools using diffusion tensor imaging and tractography are poised to make a significant impact in the clinical imaging of patients with neurological disease. Yielding structural and functional information about ordered white matter pathways in the brain, acquired and processed in a practical and efficient manner, is applicable in any setting involving the high-level practice of neuroimaging.

References


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