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Brain White Matter Tracts: Functional Anatomy and Clinical Relevance

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Diffusion tensor imaging is increasingly available on clinical magnetic resonance scanners and can be acquired in a relatively short time. There has been an explosion of applications in the research field but the use to the practicing radiologist may seem obscure. This paper aims to highlight how diffusion tensor imaging can be used to prompt a dedicated neuroanatomical search for white matter lesions in clinical presentations relating to motor, sensory, language, and visuospatial deficits. The enhanced depiction of white matter tracts in the temporal stem is also highlighted, which is a region of importance in epilepsy surgery planning.
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Introduction

Diffusion-weighted imaging (DWI) has proven to be useful in many areas of neuroimaging and is routinely applied in clinical practice. Diffusion tensor imaging (DTI), although increasingly available, is yet to find routine clinical application outside of the research environment. After briefly describing the DTI technique, this review focuses on how DTI can aid in anatomical localization of lesions and subsequently account for the clinical features that arise.

Diffusion Tensor Imaging

In routine DWI, images sensitive to the diffusion of water in brain tissue are acquired with diffusion gradients applied in 3 orthogonal planes; the signals from the 3 separate images are averaged to compensate for the effect that tissue ultrastructure has on water diffusion in any given direction. DTI allows for characterization of this underlying structure by the creation of the "diffusion tensor." The tensor describes the 3-dimensional probability distribution of water diffusion.[1] If diffusion is completely unrestricted (eg, in cerebrospinal fluid), then this distribution is spherical or *isotropic*, that is, diffusion is equally likely in each direction. In the white matter (WM), which comprises myelinated axons arranged into tracts, diffusion of water occurs relatively more easily along the course of a WM tract than directly perpendicular to it. The result is that for a WM voxel containing a single or dominant tract orientation, the diffusion distribution becomes *anisotropic* and is no longer spherical but ellipsoid, with a main axis parallel to the direction of the tract. The main axis of the ellipsoid is the principle eigenvector (e_1), with second and third eigenvectors (e_2 and e_3) oriented perpendicular to e_1 (Fig. 1). The amount of diffusion along each eigenvector is quantified as an eigenvalue ($\lambda_{1\text{-}3}$). The average eigenvalue is the mean diffusivity, a value analogous to the apparent diffusion coefficient derived by standard DWI. The tensor is calculated after probing the ease of diffusion in multiple directions; a minimum of 6 nonorthogonal, noncollinear directional experiments are required to calculate the tensor, but the more directions that are employed, the more complete the characterization of the tensor is. The penalty for increasing the number of directions is increased acquisition time. In clinical DTI, 6-32 diffusion directions are typically used, but more than 60 directions are often used in research settings.

There are a number of descriptors derived from the tensor that describe the degree of anisotropy of water diffusion, the most commonly used of which is fractional anisotropy (FA). In simple terms, this can be thought of as a measure of how much "unlike" a sphere it is or how much directionality the diffusion distribution has. An FA of 0 represents complete diffusion isotropy and an FA of 1 would represent a

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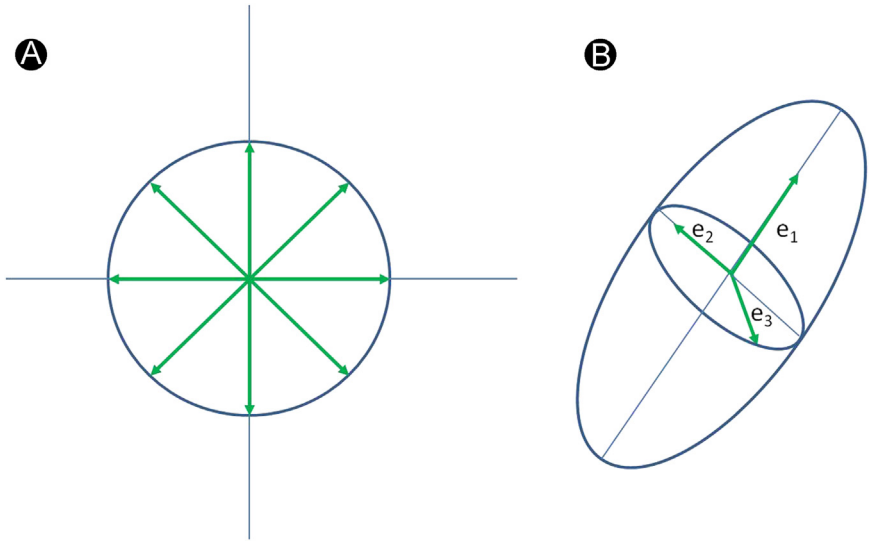

Figure 1 The diffusion tensor ellipsoid. Isotropic diffusion (A) takes the form of a sphere where the magnitude of diffusion is equal in all directions such as in CSF or cortical gray matter. Anistropic diffusion tensor represented by ellipsoid (B)—the tensor is characterized by 3 eigenvectors that have an eigenvalue or magnitude (length of arrow) and orientation (axis). The eigenvalue (λ_1) of e_1 represents the principle axis of the tensor and is thought to be a measure of axonal integrity. CSF, cerebrospinal fluid.

completely anisotropic tissue, although in practice this is not achieved. Diseases that degrade the WM ultrastructure typically lead to a reduction in the FA, and hence FA has been widely used in research settings to quantify WM damage. Other measurements derived from the tensor such as radial diffusivity and axial diffusivity are thought to reflect integrity of myelin and axonal integrity, respectively, and have been applied in research that attempts to identify different components of WM damage.[2]

In addition to representation of FA data as grayscale maps, the orientation of the diffusion ellipsoid within the voxel can be presented by the use of color coding of the voxel according to the principle eigenvector. The standard convention for color coding is as follows: red = e_1 is parallel to the x-axis of the image, green = where e_1 is parallel to the y-axis of the image, and blue = where e_1 is parallel to the z-axis of the image. A number of different methods have been described to reconstruct WM tracts from DTI images, broadly referred to as *tractography*, but the methods by which this is done fall beyond the scope of this article. However, it is worth noting that the "tracts" produced by such techniques are mathematically generated streamlines, derived from inherently limited imaging data; DTI voxels are orders of magnitude larger than the tissue ultrastructure that the technique aims to probe. Innovations such as Q-ball imaging can help to reduce uncertainties, for example, at voxels containing crossing tracts.[3] However, the streamline images generated by tractography should always be checked for plausibility against known neuroanatomy.

Neuroanatomical Correlation

Standard clinical brain imaging combined with DWI is sensitive in detecting WM pathology, but owing to the poor visualization of specific WM tracts by conventional imaging, it does not always reveal the WM structures that are affected by the pathology detected. The following section reviews which WM structures should be assessed in various different clinical presentations and how DTI can help answer the frequent clinical question: "Does this lesion account for clinical presentation?"

Motor Syndromes

The corticospinal tract (CST) conveys efferent WM projection fibers between the motor cortex and the spinal cord, enabling voluntary movement. The tract predominantly originates from the primary motor cortex (Brodmann area 4) but also includes fibers from the premotor and supplementary motor cortices (area 6), the somatosensory cortex (areas 1, 2, 3a, and 3b), and the superior parietal lobule (area 5).[4] These WM fibers converge and descend through the corona radiata, the posterior limb of the internal capsule (PLIC), the central portion of the cerebral peduncle, and the ventral aspect of the pons, before decussating in the medullary pyramids and descending within the spinal cord[5-7] (Fig. 2).

Face, Arm, and Leg Weakness

The somatotopic arrangement of the primary motor cortex is preserved in the CST, which conveys efferent WM projection fibers between the motor cortex and the spinal cord, enabling voluntary movement. Thus, the motor components of cortical middle cerebral artery or anterior cerebral artery territory infarction (face, arm, or leg weakness) can be reproduced by lesions at different points along its course.

Infarcts in the centrum semiovale may be large, presenting with all of the aforementioned middle cerebral artery features but are more commonly lacunar with upper limb weakness