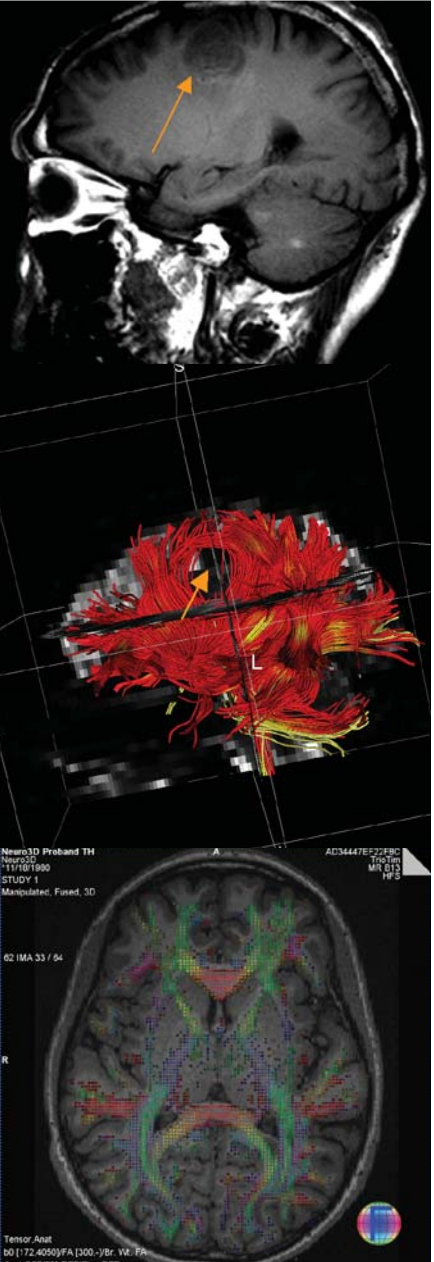

Diffusion Tensor Imaging

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Diffusion Tensor Imaging

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Introduction

Diffusion tensor imaging (DTI) represents the next generation of diffusion weighted imaging (DWI) in MR. Diffusion weighted imaging non-invasively looks at the restriction of random Brownian motion of tissue water and provides clues about the microenvironment in which the water molecules are dispersing. Disease may directly or indirectly change the diffusion characteristics of the underlying tissue and can therefore be detected using diffusion weighted imaging techniques. For example, the failure of the sodium-potassium ATP pump causes cytotoxic edema following acute brain infarction. This process shifts extracellular fluid into the intracellular space in the affected area showing changes in the signal intensities on MR images as compared to the unaffected brain tissue.

In the brain, water cannot diffuse as freely in all directions as surrounding tissue structures limit their mobility, hence creating preferred directions of diffusion. For example, it is easier for water to diffuse along the length of a white matter fiber rather than across the fiber. This property, known as diffusion anisotropy, is physically linked to the anisotropy of the tissue structure.

Standard DWI acquires data in three orthognal planes (typically X, Y, and Z axis). The signal intensity of diffusion weighted images depends on the pulse sequence used, the T2 of the underlying tissue and the diffusion characteristics of that tissue. Because of this complexity, DWI can be difficult to interpret in conditions where the underlying T2 is altered. A set of images called ADC (apparent diffusion coefficient) maps help in these situations. ADC maps are created by combining information from diffusion weighted images and information from images obtained from the same pulse sequence, but with low or no diffusion gradients "ON" (low b-value) to reduce the T2 contributions from tissue also called the "T2 shine thru effect". The signal intensities of diffusion weighted images and ADC maps are very different. A decrease in ADC causes increased signal intensity on DWI, but decreased signal intensity on ADC maps (See Figure 1).

Diffusion, however, is a three-dimensional process. In order to acquire more detailed information about anisotropic diffusion properties of the underlying tissue, simple standard DWI is not sufficient. While ADC maps reveal the tendency of the water molecules to diffuse within a voxel, directional variation is also required to image 3D anisotropic diffusion. The complex mathematical equation used to model 3D anisotropy is called tensor. By sampling 6 or more diffusion directions and establishing a relationship between the acquired data and applied diffusion gradients in the pulse sequence, the directional variation in the tendency of water molecules to diffuse within a voxel can be imaged. This technique is called DTI. It describes the diffusion along each direction and interactions between the directions providing important information about tissue connectivity. It can be utilized for example, to investigate the white matter structure of the brain and the changes that occur in association with the disease process in vivo. Fiber tracking or tractography is the process of tracing

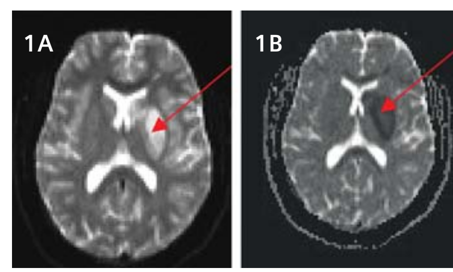

Figure 1A: DWI in case of infarct. Figure 1B: ADC map in the same case. Please note the signal intensity differences between DWI and ADC.

the three-dimensional course of white matter fiber tracts using DTI data sets. This can be used to document integrity, displacement or involvement of white matter tracts in different clinical conditions like trauma or tumors and predict outcome of treatment. While in theory the acquisition of 6 diffusion directions is sufficient to calculate the tensor information in each voxel, the higher the number of directions the more robust the tensor calculation will be, but the longer the scan will take. Thus, there is always a trade-off between the acquisition time and robustness. As described in the literature, the number of diffusion directions typically being used is in the order of 20–30.

While the full applicability of this emerging technique is still under investigation, clinically relevant applications are becoming apparent including pre-surgical planning and evaluation of brain tumors (see Figure 2).

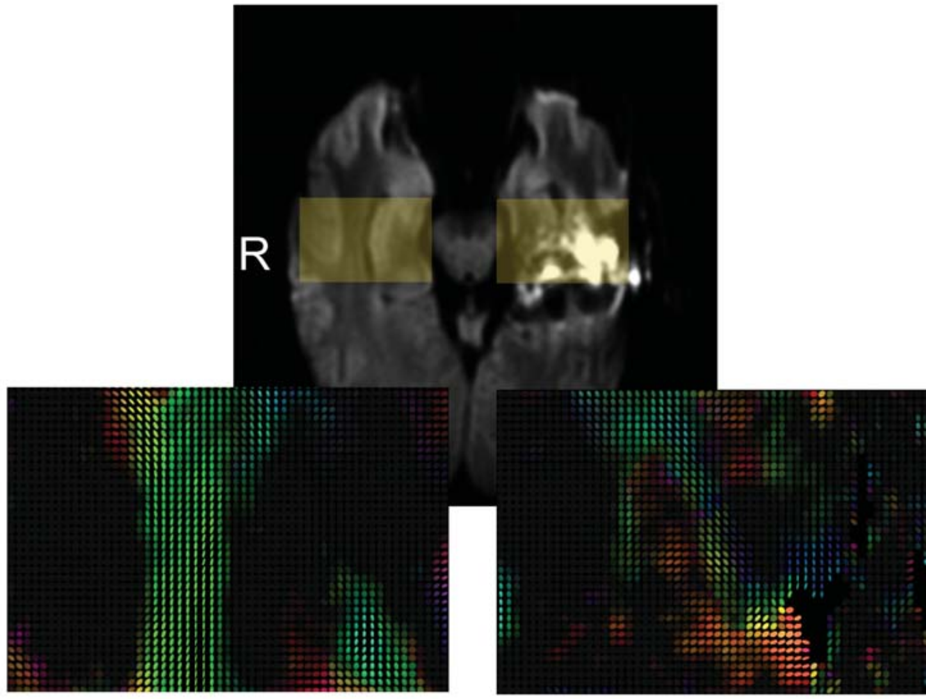

Figure 2. An example from a patient with a high-grade glioblastoma. The boxed regions on the DTI image are zoomed. The right side demonstrates typical healthy white matter where the fiber tract orientations are clearly visible in the DTI image. In the region of the tumor, a very obvious disorganization of the tissue is observed at a level of detail beyond the standard grayscale DWI image. Courtesy of Shella Kielholtz, PhD, and Tim Fox, PhD, at Emory University in Atlanta.

Analysis and Indices from DTI datasets

From the DTI data several other diffusion maps or indices can be calculated. Commonly utilized indices are FA (fractional anisotropy), which relates to the directionality in the voxel, ADC (apparent diffusion coefficient), which is a quantitative measure independent of imaging parameters and TraceW (trace weighted), which shows overall water displacement. The latter two measures are comparable to that obtained with standard DWI, yet are derived from the entire DTI dataset enabling directional representation.

Fractional Anisotropy (FA)

Fractional Anisotropy (FA) is one of the most important DTI indices available to the clinicians. This index relates to the level of organization of the tissue microstructure. In the developing brain for instance, changes in T1 and T2 signals are seen later than directional bias as measured by FA, hence FA is an excellent marker for white matter organization. In highly directional tissues such as white matter tracts or skeletal muscle one would expect a high FA value. Some potential pediatric applications where this would be beneficial are characterizing normal myelination and leukodystropies. In gray matter a low FA value is measured since the tissue structure is not organized into fibers and is generally isotropic. An example FA map is shown in Figure 3A. As shown, a further level of detail can be displayed by color-coding directionality on the FA map. This image now shows not only the location of large white matter tracts but also their prevalent direction using the tensor information.

Apparent Diffusion Coefficient (ADC, Trace)

Measurement of the diffusion coefficient from the DTI data gives an indication of the mobility of water in the tissue. Large values of ADC are indicative of free water while smaller values imply that water mobility is constrained by the local tissue environment. An example ADC image is shown in Figure 3B. Using the tensor model the ADC is calculated as the trace of the diffusion tensor by averaging the diagonal elements. This calculation yields the mean diffusivity, or ADC in the tissue, which is independent of the diffusion encoding.

TraceW

The trace-weighted image is obtained by taking the geometric average of the individual diffusion weighted images from the DTI scan. This generates an image comparable to orthogonal DWI, yet is derived from the full diffusion

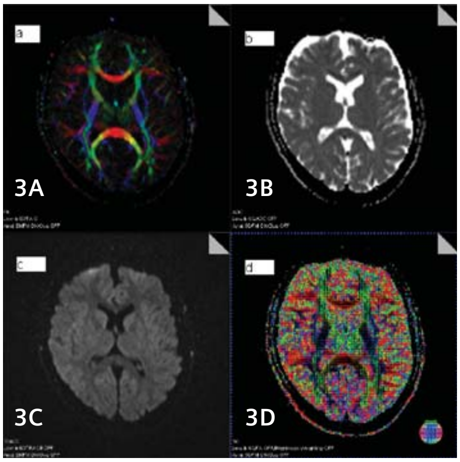

Figure 3: Different diffusion maps (indices) calculated like FA, ADC and Trace weighted images.

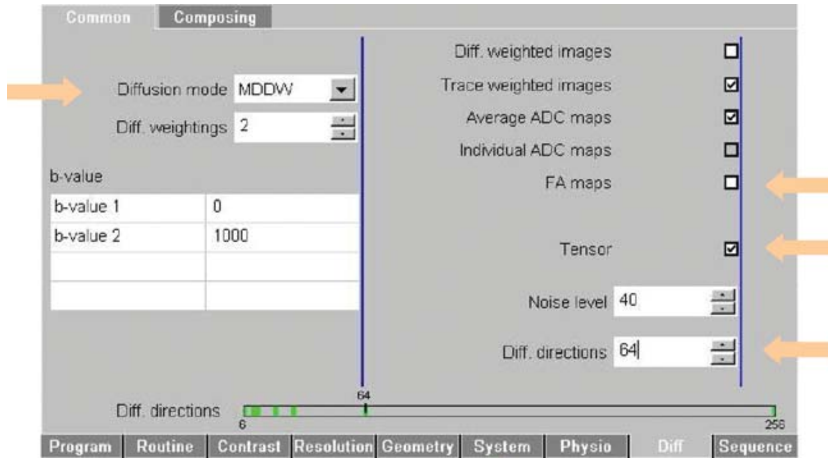

Figure 4: A syngo MR exam task card showing the different user-selectable Diffusion parameters and "Inline" map creation (cream arrows).

sampling. This image has a contrast reversal as compared to the ADC image, hence the notation as trace-weighted. An example TraceW image is shown in Figure 3C.

DTI can *syngo*!—Siemens Solution

For diffusion weighted imaging, the Tim Application Suite and the Inline Diffusion option are required on all Tim systems to enable state-of-the art Diffusion imaging with inline calculation of ADC maps and Trace images. These two packages have been included as standard configuration in the US. This simplifies workflow and improves efficiency.

DTI is an advanced application. On all 1.5T and 3T Siemens MAGNETOM systems 6 and 12 directional tensor capabilities, referred to as Multi-Direction Diffusion Weighted sequence, or MDDW, are available in the optional Advanced Functional Neuro package. Post processing of the DTI data prior to the release of B13 software was available through a Siemens collaboration partner.

Optional stand alone DTI Imaging and DTI evaluation package became available starting with B13 software for Tim systems. The acquisition and analysis of DTI data have been enhanced allowing calculation and visualization of inline FA and Tensor maps. Now up to 256 diffusion directions can be acquired and various maps can be generated inline, "on-the-fly".

While collecting diffusion tensor information and post processing to create the maps may sound like a significant undertaking, *syngo* delivers this advanced capability in an easy to use tool. All parameters can be selected with a single mouse click and the maps are available in grey scale in real-time without any additional user intervention (see Figure 4). There are wide ranges of diffusion maps that may be created from tensor data (Figure 5), including:

- Apparent Diffusion Coefficient
- Fractional Anisotropy
- Volume Ratio
- Trace Weighted
- Eigen Value Maps
- Linear and Planar Maps
- Tensor Maps

The tensor data can be displayed either as color coded pixels or in an ellipsoid representation.

For advanced research applications multiple b-values can also be sampled, which is necessary for Diffusion Spectroscopic Imaging (DSI). Once the tensor data is acquired, detailed representation of the underlying tissue may be visualized by applying specialized mathematical models to the acquired data.

Color and DTI Analysis and Image Fusion

For advanced neuro imaging it is often the preference to view the data with color representation. The *syngo* Neuro3D taskcard available with the Advanced Functional Neuro Package is enhanced by the optional DTI Evaluation package by allowing the generation of color analysis maps desired for displaying directional information of the neuro fibers. Additionally, the DTI Evaluation package allows fusion of fMRI data with DTI and anatomical images. Fusion of fMRI data with DTI data onto anatomical 3D dataset from the same patient is possible, providing a comprehensive assessment of all areas of concern for neuro surgical planning.

Applications

DTI Complements BOLD fMRI

Functional localization in the cortex using BOLD fMRI has become standard practice in neuro-imaging. By integrating DTI data, cortical networks can be associated with white matter networks.

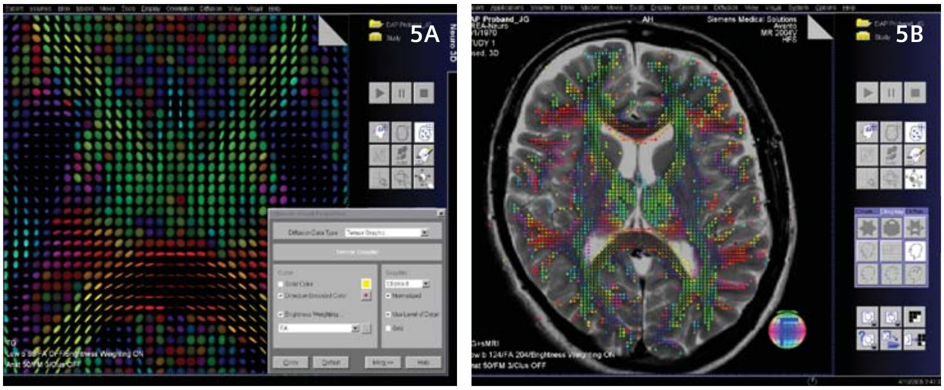

Figure 5A: A screen-shot of 3D Neuro task card showing the different colorized diffusion maps responded by offering a complete solution. (Tensor Graphics). Figure 5B: side-by-side display of diffusion maps and anatomy.

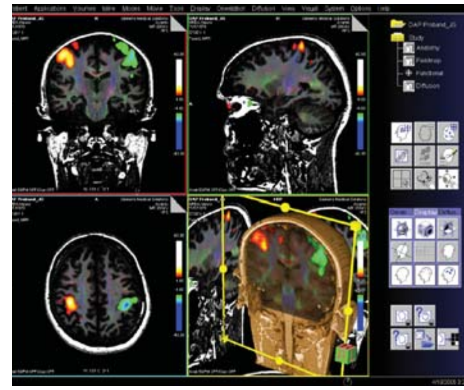

Figure 6: Image fusion of anatomical image, DTI data and fMRI BOLD results.

Using image fusion these two sources of information can be overlaid on structural T1 scans generating a composite structural and functional picture of brain networks. Figure 6 shows an example of this image fusion using the 3D Neuro task card.

DTI Evaluation of Brain Tumors

DTI complements traditional neuroimaging techniques in oncology by providing additional contrasts to evaluate the disease mechanism.

1. Better differential diagnosis by providing more information:
   a. Epidermoid tumors may be difficult to differentiate from arachnoid cysts only with imaging due to similar signal characteristics. ADC maps of epidermoid tumors are hypointense while the ADC maps of arachnoid cysts are hyperintense.
   b. DWI may help in distinguishing between intracerebral abscess and a cystic tumor.
   c. Diffusion MR may help discriminate lymphoma from toxoplasmosis
2. Better treatment planning by grading tumors accurately:
   a. ADCs are lower in grade II and III meningiomas as compared to grade I meningiomas thus helping to establish prognosis and treatment planning.
   b. Similarly in the case of gliomas, high-grade gliomas have decreased ADCs.
3. Better patient care by quality follow-up.
   a. DTI is used in treatment planning and better prediction of treatment outcomes
   b. Tractography and intra-operative MR improve to define resection access and area, thus reducing post-op complications.
   c. Post-treatment follow-up for residual tumor
   d. Detecting recurrence
   e. And early detection of complications (acute infarcts along surgical margins or post-radiation vasculopathy, from chemotherapy or radiation therapy).

All this may help in quality follow-up and guide prompt intervention, improving patient care and speed recovery.

Lesion Burden Better Quantified by DTI in Multiple Sclerosis (MS)

The quantification of MS lesion burden is an integral tool for tracking the disease progression in MS. Prior techniques using T2-weighted volumetrics have been shown to lack correlation with clinical measures. Using DTI scanning the disease burden can be more accurately quantified.

DTI is an Important Tool in Neuro Science Research

The ability to document integrity of tracks makes DTI an important tool in neuro science research. This information is complementary to fMRI. DTI is extensively used to study pathogenesis of white mater disease and to understand aging.

Conclusion

Diffusion tensor imaging is a powerful tool for investigating the tissue microstructure. Finding new clinical applications for DTI is a hot topic in the MR research community. Siemens has recognized the need for a robust DTI package and responded by offering a complete solution.

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