Role of diffusion tensor MR imaging (DTI) and fiber tractography in preoperative assessment of brain tumours

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Learning objectives

- To be aware of the MRI anatomy of the brain white matter tracts.
- To highlight the important role of DTI in preoperative assessment of the WM tracts in patients with brain tumors thus minimizing the injury of WM tracts and avoiding postoperative neurological deficits.
- To study the different patterns of WM tract involvement by tumors.
Background

• The recent advances in brain tumor imaging offer unique anatomical as well as pathophysiological information that provides new insights on brain tumors, directed on facilitating new therapeutic decisions and proving information regarding the prognosis. The newer advances include MRI diffusion and tensor imaging with tractography, perfusion imaging, MR spectroscopy and functional imaging using BOLD (1).

• Although routine structural MR images can accurately demonstrate brain tumors, they do not give precise information about the involvement and integrity of the white matter tracts in the immediate region surrounding tumors. Magnetic resonance diffusion tensor imaging (DTI) is the most powerful and currently the only way to visualize the organization of white matter fiber tracts in-vivo (2).

• Knowledge of the structural integrity and location of eloquent white matter tracts relevant to cerebral tumors is crucial in neurosurgical planning, because damage to these clinically eloquent pathways can result in postoperatively neurological deficits as damage of functional cortical areas. Consequently, it is very important for designing appropriate neurosurgical plan that determines the exact location of tumors relevant to eloquent white matter tracts (3).

• Neurosurgery for a brain tumor is a trade-off between maximum surgical resection on one hand and maximum sparing of functions on the other hand. Extensive tumor resection can reduce the risk of relapse (particularly gliomas with low grade malignancy) and allow subsequent radiotherapy or chemotherapy to be more effective. On the other hand, sparing "functionally relevant" zones and therefore preservation of motor, visual or language functions significantly improves the quality of life of these patients (4).

Physical Background

• Understanding the physics of DTI and tractography involves several complex mathematical calculations and formulae. In brief, diffusion imaging is an MRI imaging technique that is sensitized to the Brownian motion of water molecules in biological tissues. A diffusion weighted (DW) sequence can be produced by adding a magnetic field gradient of equal magnitude and duration prior to and after the 180-degree refocusing pulse. A routine DW sequence with ADC (apparent diffusion coefficient) provides a measure of the displacement of water molecules in one direction (5).

• For DTI, several directions are required, as white matter in the brain is anatomically present in different directions. Diffusion in the brain is not uniform but anisotropic, along the direction of the various fiber tracts.
Therefore, the measure of diffusion cannot be represented as a single quantity but is modeled by estimation of a diffusion tensor (D), which is the measurement of water diffusion in different directions. At least six non collinear directions and an image without diffusion weighting are needed in order to calculate D. From this, the tensor ‘eigenvalues and eigenvectors’ can be derived. The eigenvalues represent the magnitude of diffusion, whereas eigenvectors represent the corresponding direction. The diffusion tensor can be conveniently visualized by a diffusion ellipsoid \(^{(5)}\) \textbf{Fig. 1 on page 6}

- Information from DTI is presented in two formats, which are FA (fractional anisotropy) maps and tractography. FA maps are crosssectional images that may be in a gray scale format or may be color coded for directional information \textbf{Fig. 2 on page 6}. FA stands for fractional anisotropy. Structures that have anisotropy, that is, white matter, appear bright on the gray scale FA maps and the degree of brightness is proportional to the anisotropy. When a white matter tract is destroyed by say a tumor, there is loss of anisotropy and therefore a reduction in the FA values, which is manifested on the gray scale FA maps, as loss of brightness. FA values can also be quantified numerically \(^{(1)}\).

- The anisotropic part of diffusion in a tissue is measured by fractional anisotropy (FA), which is a rotationally invariant scalar index of the amount of anisotropy. It scales from 0 (no diffusion) to 1 (diffusion in one direction only). Therefore, high FA values represent a high degree of directionality in the white matter tracts compared to grey matter, where the FA values are low. Even in white matter, there are strong variations of anisotropy measures between different brain regions, with the highest measures seen in the corpus callosum and the pyramidal tract. These FA values will alter in any area where there is a focal brain lesion, causing alteration in the white matter tract. This is the principle which was utilized in the application of FA maps in focal brain lesions \(^{(5)}\).

- Color FA maps are obtained, where the color intensity is scaled in proportion to the magnitude of FA. From these FA maps, DTI-based color-coded maps can also be generated. In these maps, colors are chosen according to the high eigenvector associated with the largest eigenvalue. In most MRI machines, red is assigned to the x-direction (left to right), green to the y-direction (anterior-posterior), and blue to the z-direction (superior-inferior) \(^{(5)}\).

\textit{Anatomical Background: (Types of white matter tracts)} \(^{(6)}\)

- \textbf{Association fibers} \textbf{Fig. 3 on page 7}: interconnect cortical areas in each hemisphere. Fibers of this type typically identified on DTI color maps include:
1. Superior longitudinal (arcuate) fasciculus.
2. Inferior longitudinal (occipitotemporal) fasciculus.
5. Uncinate fasciculus.

- **Projection fibers Fig. 4 on page 8**: interconnect cortical areas with deep nuclei, brain stem, cerebellum, and spinal cord. Fibers of this type typically identified on DTI color maps include:
  1. Corticospinal tract.
  2. Corticopontine tract.
  3. Optic radiation.
  4. Thalamic radiations.

- **Comissural fibers Fig. 5 on page 9**: interconnect similar cortical areas between opposite hemispheres. The largest and most important fibers of this type identified on DTI color maps is the corpus callosum.

- **Tracts in the brainstem Fig. 6 on page 10**
Line diagram demonstrating the concept of isotropic diffusion, which results from the free random movement of protons (arrow) producing a circle (bold arrow). However, in the brain, due to the presence of various fiber tracts, the movement of protons is restricted, resulting in anisotropic diffusion (ellipsoid) (shown in the lower half of the figure)

Fig. 1

A, FA map without directional information. B, Combined FA and directional map. Color hue indicates direction as follows: red, left-right; green, anteroposterior; blue, superior-inferior. This convention applies to all the directional maps in this review. Brightness is proportional to FA.

Fig. 2

Fig. 3: Association fibers

Fig. 4: Projection fibers

Fig. 5: 3D of the corpus callosum

**Fig. 6:** Tracts in the brain stem

Findings and procedure details

**Technique for presented cases:**

- MRI was done without prior preparation or anesthesia and after the exclusion of MRI contraindications as cardiac pace maker, claustrophobia etc.
- Technique was performed using a standard 1.5 Tesla unit (Intera and Achiva, Philips). A standard head coil was used.
- The sequences obtained were axial T1W, T2W, FLAIR, DW and Diffusion Tensor.
- Diffusion Tensor consisted of a single shot, spin-echo echoplanar sequence in 12 encoding directions. A diffusion weighting factor of 800 s/ mm². TR 8000 ms, TE 67 ms, Flip angle 90#, matrix 112 x 110, FOV 210 x 236 mm, number of excitations: 2, slice thickness: 2.0/00
- All the images were transferred to the workstation (Phillips Extended MR Workspace, 2.6.3.5 Netherlands) for post processing.
- The maps obtained were
  1. FA maps.
  2. directionally-encoded color FA maps.
  3. 3D fiber tractography maps.

**Interpretation:**

We adopted the criteria developed by Cruz et al\(^{(7)}\) to classify fiber tract involvement into 4 categories:

1. **Deviation (Displaced):** if the tract showed normal or only slightly decreased FA, with abnormal location and/or direction, resulting from bulk mass displacement.
2. **Edematous:** if the tract maintained normal or slightly reduced anisotropy with normal orientation but demonstrated high signal intensity on T2WI.
3. **Infiltrated:** if the tract showed substantially decreased FA with abnormal hues on directional color maps and remained identifiable on color maps.
4. **Destructed (Disrupted):** if the tract showed isotropic (or near isotropic) diffusion, such being no more identified on directional color maps.

**Cases:**

1. **Case 1:** A female patient, 42 year old with right cerebellopontine angle space occupying lesion. The tumour is seen displacing the right corticospinal tract and right middle cerebellar peduncle [Fig. 7 on page 14 and Fig. 8 on page 14]
2. **Case 2:** A male patient, 60 year old with right frontal space occupying lesion. There's destruction of the right anterior fibers of the body of the corpus callosum. [Fig. 9 on page 15 and Fig. 10 on page 16]
3. **Case 3:** A male patient 53 year old with right frontoparietal SOL. there's destruction of the right corona radiata and body of the corpus callosum. [Fig. 11 on page 17](#) [Fig. 12 on page 18](#) and [Fig. 13 on page 19](#)
4. **Case 4:** Female patient 60 year old with left fronto-temporo-parietal lesion. Tractography showed displacment of the left side major tracts by the mass effect of the tumour [Fig. 14 on page 19](#) [Fig. 15 on page 20](#) [Fig. 16 on page 21](#) , [Fig. 17 on page 22](#) and [Fig. 18 on page 23](#)
5. **Case 5:** Male patient 58 year old with right temporal space occupying lesion. there's destruction of the right tapetum, displacement of the other major white matter tracts on the right side [Fig. 19 on page 24](#) [Fig. 20 on page 25](#) [Fig. 21 on page 26](#) and [Fig. 22 on page 27](#)
Images for this section:

**Fig. 7:** case 1

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- Axial T1 +C shows right CPA mass lesion
Fig. 8: case 1 MCP (middle cerebellar peduncle) CST (corticospinal tract)

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Axial T1 +C shows right frontal mass lesion with mild perifocal edema.

Fig. 9: case 2

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Fig. 10: case 2

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Axial Diffusion WI at b0 shows right frontoparietal mass lesion crossing the midline.

**Fig. 11**: case 3

Tractography of the CC showing destruction of the anterior part of its body by the tumor
Fig. 12: case 3

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Tractography of the CST and corona radiata showing destruction of the anterior fibers on the right side (red) compared to the left side (blue)

Fig. 13: case 3

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Fig. 14: Case 4: Axial T2 shows left fronto-temporo-parietal space occupying lesion

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Fig. 15: Case 4: displacement of the left superior longitudinal fasiculus (SLF) which is seen splayed along the superior aspect of the lesion.

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Fig. 16: Case 4: displacement of the left CST medially and it is seen splayed along the superior aspect of the lesion.

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**Fig. 17:** case 4: 3D fiber tractography of the left side major tracts related to the tumour showing: displaced SLF upward (purple), CST medially (blue), inferior fronto occipital fasiculus (IFOF) medial and superiorly (yellow) and the inferior longitudinal fasiculus (ILF) inferior and laterally (arrowed yellow).

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Fig. 18: case 4: 3D fiber tractography of the left side major tracts related to the tumour showing: displaced SLF upward (purple), CST medially (blue), inferior fronto occipital fasiculus (IFOF) medial and superiorly (yellow) and the inferior longitudinal fasiculus (ILF) inferior and laterally (arrowed yellow).

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Fig. 19: case 5: Axial FLAIR image showed right temporal space occupying lesion.
Fig. 20: Case 5: 3D tractography of the corpus callosum showing destruction of the right tapetum.

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**Fig. 21:** case 5: 3D fiber tractography of the right side major tracts related to the tumour showing: displaced inferior fronto occipital fasiculus (IFOF) posterior and superiorly (blue) and the inferior longitudinal fasiculus (ILF) inferior and laterally (red) as well as the corticospinal tract (CST) medially (purple).

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Fig. 22: case 5: 3D fiber tractography of the right side major tracts related to the tumour showing: displaced inferior fronto occipital fasiculus (IFOF) posterior and superiorly (blue) and the inferior longitudinal fasiculus (ILF) inferior and laterally (red) as well as the corticospinal tract (CST) medially (purple). note the right arcuate fasiculus (yellow) is displaced upwards

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Conclusion

In the current clinical practice, one of the most important applications of DTI is to study the relation of a tumor to the adjacent white matter tracts. White matter involvement by a tumor can be arranged into various categories with DTI, such as, deviated, infiltrated, edematous, and destroyed white matter tracts. This helps in the pre surgical planning and aims to maximum tumour resection and to minimize injury to the white tracts and thus avoid postoperative neurological deficits.
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