White Matter Anatomy
What the Radiologist Needs to Know

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KEYWORDS

• Diffusion tensor imaging (DTI) • White matter tracts • Projection fibers • Association Fibers
• Commissural fibers

KEY POINTS

- Diffusion tensor imaging (DTI) has emerged as an excellent tool for in vivo demonstration of white matter microstructure and has revolutionized our understanding of the same.
- Information on normal connectivity and relations of different white matter networks and their role in different disease conditions is still evolving. Evidence is mounting on causal relations of abnormal white matter microstructure and connectivity in a wide range of pediatric neurocognitive and white matter diseases.
- Hence there is a pressing need for every neuroradiologist to acquire a strong basic knowledge of white matter anatomy and to make an effort to apply this knowledge in routine reporting.

INTRODUCTION

DTI has allowed in vivo demonstration of axonal architecture and connectivity. This technique has set the stage for numerous studies on normal and abnormal connectivity and their role in developmental and acquired disorders. Referencing established white matter anatomy, DTI atlases, and neuroanatomical descriptions, this article summarizes the major white matter anatomy and related structures relevant to the clinical neuroradiologist in daily practice.

MR IMAGING OF WHITE MATTER TRACTS

White matter is seen well on the T1, T2, and fluid-attenuated inversion recovery (FLAIR) sequences used in routine MR imaging. Certain white matter tracts are reasonably well demonstrated particularly on T2 and FLAIR images[1] because of their location and in the pediatric age group, because of the differences in water content and myelination (**Fig. 1**). However, the use of specific DTI sequences provides far more detailed and clinically useful information.

DIFFUSION TENSOR IMAGING: THE BASICS

Using appropriate magnetic field gradients, diffusion-weighted sequences can be used to detect the motion of the water molecules to and from cells. This free movement of the water molecules is random and thermally driven in neurons. In the axons, the axonal membranes and myelin sheaths act as barriers to the random motion of the water molecules, and this motion thus becomes directionally dependent or anisotropic, with the direction of maximum diffusivity aligning with the direction of white matter tract orientation.[2] With DTI, this degree of anisotropy and fiber direction can be mapped voxel by voxel, allowing for the in vivo assessment of white matter tract architecture.

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Neuroimag Clin N Am 23 (2013) 197–216
http://dx.doi.org/10.1016/j.nic.2012.12.002
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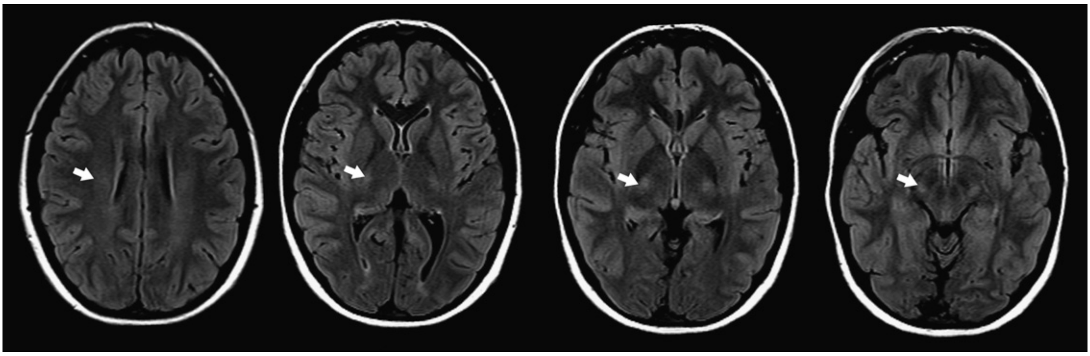

Fig. 1. Axial FLAIR images in a normal 14-year-old boy show that the corticospinal tract is mildly hyperintense, as marked with white arrows.

A diffusion tensor is a mathematical model containing diffusion measurements from at least 6 noncollinear directions, from which diffusivity in any direction as well as the direction of maximum diffusivity can be estimated.[3] Using more than 6 encoding directions will improve the accuracy of the tensor measurements,[4] and DTI is more often obtained with 30 to 60 directions. The tensor matrix is ellipsoid, with its principal axis oriented in the direction of maximum diffusivity. Via a linear algebraic procedure called matrix diagonalization, 3 *eigenvalues* are obtained, which represent apparent diffusivity in the 3 principal axes of the ellipsoid, namely the *major*, *medium,* and *minor* axes, also known as the *eigenvectors*.[3]

The *x*-, *y*-, and *z*-coordinate system to which the scanner is oriented is rotated to a new coordinate system, dictated by diffusivity information. Fractional anisotropy (FA) is derived from the standard deviation of the 3 eigenvalues and ranges from 0 (isotropy) to 1 (maximum anisotropy). The orientation of maximum diffusivity may be mapped using red, green, and blue color channels and color brightness, modulated by FA, and this can result in the formation of a color map demonstrating the degree of anisotropy and local fiber direction.

The conventional color coding is green for fibers oriented anteroposterior (mainly the association fibers), red for right–left oriented fibers (mainly commissural fibers), and blue for superior–inferior fibers (in particular as projection fibers). In 2D images (**Fig. 2**), mixed color is seen when fibers overlap, resulting in yellow (green and red), magenta (red and blue), and cyan (green and blue), and with changes in orientation (see **Fig. 2**).[5]

CLASSIFICATION OF WHITE MATTER TRACTS

The white matter tracts are broadly classified into 3 groups according to their connectivity (**Table 1**):

1. *Projection fibers*: These fibers connect the cortical areas with the deep gray nuclei, brainstem, cerebellum, and spinal cord or vice versa. Corticospinal fibers, corticobulbar fibers, corticopontine fibers, thalamic radiations, and geniculocalcarine fibers (optic radiations) are tracts identifiable on DTI.
2. *Association fibers*: These fibers connect different cortical areas within the same hemisphere. The fibers can be long range or short range, the latter including subcortical U fibers. The major long tracts include cingulum, superior and inferior occipitofrontal fasciculus; uncinate fasciculus; superior longitudinal fasciculus (SLF), including arcuate fasciculus; and inferior longitudinal fasciculus (occipitotemporal).
3. *Commissural fibers*: These fibers connect similar cortical areas in the 2 hemispheres, including the corpus callosum and the anterior commissure.

Other tracts and fibers, which can be seen in DTI maps, include the optic pathway, fornix, and many fibers within the cerebellum and brainstem. These tracts and fibers are described separately.

PROJECTION FIBERS

Projection fibers are afferent and efferent tracts that interconnect areas of the cortex with the brainstem, deep nuclei and cerebellum, and spinal cord. Of these, the main ones identifiable on DTI include the corticospinal, corticobulbar, corticopontine, and geniculocalcarine tracts (optic radiations).

Corticospinal Tracts

Corticospinal tracts are descending projection tracts connecting the motor area to the spinal cord (see **Fig. 2**; **Fig. 3**). Corticospinal tracts have long been believed to arise from the motor

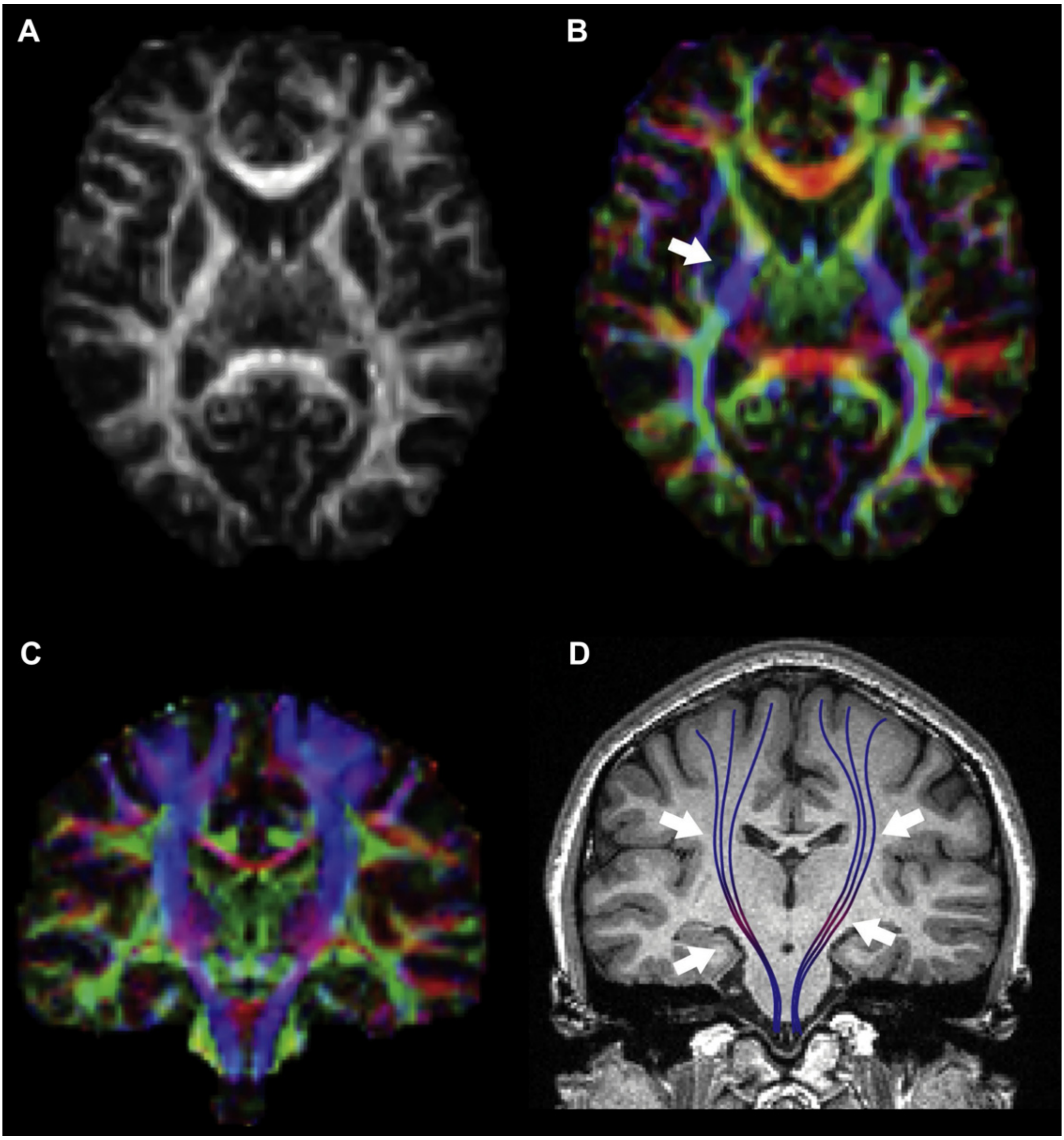

Fig. 2. Fractional anisotropy (*A*) and corresponding color maps (*B* and *C*) and Coronal T1 with schematic overlay of the corticospinal tract (*D*). Note that the horizontal fibers of the genu and splenium of the corpus callosum at this level are represented in red, whereas the vertically orientated corticospinal tracts in the posterior limb are represented in blue (*arrow, B*). Anteroposterior fibers such as the SLF are represented in green (*B*). Likewise because the corticospinal tracts enter the cerebral peduncles and take a medial course, their color value mixes red and blue into magenta (*arrows, D*).

cortex of the precentral gyrus. In a study of 42 healthy children using DTI, Kumar and colleagues[6] showed that the fibers originate in both precentral and postcentral gyrus in 71% of older children, followed by precentral gyrus, and least commonly from the postcentral gyrus. This pattern was not influenced by hand preference.

From the cortices, the fibers converge into the *corona radiata*. Here the more anterior fibers represent those servicing the face and the posterior fibers represent those that connect to the lower limb with fibers in between representing the hand.[7] Fibers then occupy the posterior aspect of the *posterior limb of internal capsule* (PLIC), beginning more anteriorly at the middle of the PLIC and then shifting more posteriorly as the tracts descend. Fibers representing the hand are anterior to those of the feet.[2]

At the level of the cerebral peduncles, the corticospinal tracts occupy the middle third of the *crus*

Table 1
White matter tracts, their connections and main functions

White Matter Tracts	Connection	Function
Cingulum	Cingulate gyrus to the entorhinal cortex	Affect, visceromotor control; response selection in skeletomotor control; visuospatial processing and memory access
Fornix	Hippocampus and the septal area to hypothalamus	Part of the Papez circuit; critical in formation of memory; damage or disease resulting in anterograde amnesia
Superior longitudinal fasciculus	Frontotemporal and frontoparietal regions	Integration of auditory and speech nuclei
Inferior longitudinal fasciculus	Ipsilateral temporal and occipital lobes	Visual emotion and visual memory
Superior fronto-occipital fasciculus	Frontal lobe to ipsilateral parietal lobe—name being a misnomer	Spatial awareness, symmetric processing
Inferior fronto-occipital fasciculus	Ipsilateral frontal and occipital, posterior parietal and temporal lobes	Integration of auditory and visual association cortices with prefrontal cortex
Uncinate fasciculus	Frontal and temporal lobes	Auditory verbal and declarative memory
Thalamic radiations	Lateral thalamic nuclei to cerebral cortex through internal capsule	Relay sensory and motor data to precentral and postcentral cortex
Corticofugal fibers (descending projection fibers)	Motor cortex and cerebral peduncle through internal capsule	Descending motor fibers from primary motor cortex, ventral and dorsal premotor areas, and supplementary motor areas
Corpus callosum	Corresponding cortical areas of both hemispheres	Interhemispheric sensorimotor and auditory connectivity
Anterior commissure	Olfactory bulbs and nuclei and amygdala	Integral part of the neospinothalamic tract for nociception and pain sensation

Adapted from Hutchins T, Herrod HC, Quigley E, et al. Dissection of the white matter tracts: interactive diffusion tensor imaging teaching atlas. University of Utah, Department of Neuroradiology. Available at: http://www.asnr2.org/neurographics/7/1/26/White%20Matter%20Tract%20Anatomy/DTI%20tutorial%202.html. Accessed July 15, 2012.

cerebri. Here the face fibers run medial to the fibers representing the feet, with the fibers representing the hand once again in between.[8] The fibers travel within the *basis pontis* before passing through the anterior medulla, forming *the medullary pyramids*. At the level of the caudal medulla, most of the fibers (75%–90%) in the pyramids cross to the contralateral side, forming the *pyramidal decussation of Mistichelli*. These fibers then descend as *the lateral corticospinal tract* within the posterior part of the *lateral funiculus* of the *medulla spinalis*. Of the fibers that do not cross, the majority travel in the anterior column on either side of the median fissure as the *anterior corticospinal tracts*, historically known as the *bundle of Türck*. These tracts decussate where they terminate, at their respective spinal level within the contralateral anterior horn gray matter.[7]

There are variations in this anatomy with some fibers not crossing to form ipsilateral lateral corticospinal tracts and others decussating to form contralateral anterior corticospinal tracts. Approximately 2% of the corticospinal tract remains truly ipsilateral, running in the ventrolateral funiculus as the bundle of Barnes to supply axial muscles of the trunk and proximal limbs.[9]

Likewise, there may be some asymmetry in the corticospinal tracts. The left corticospinal tract has higher FA values and lower transverse diffusivity because of high myelin content.[4] There is an increase in FA within the corticospinal tracts with increasing age.[6] Partially uncrossed pyramidal tracts are very rare (**Fig. 4**) and have been described by Alurkar and colleagues[10] and have been described with horizontal gaze palsy and scoliosis by Mori and colleagues[11] in 2005.

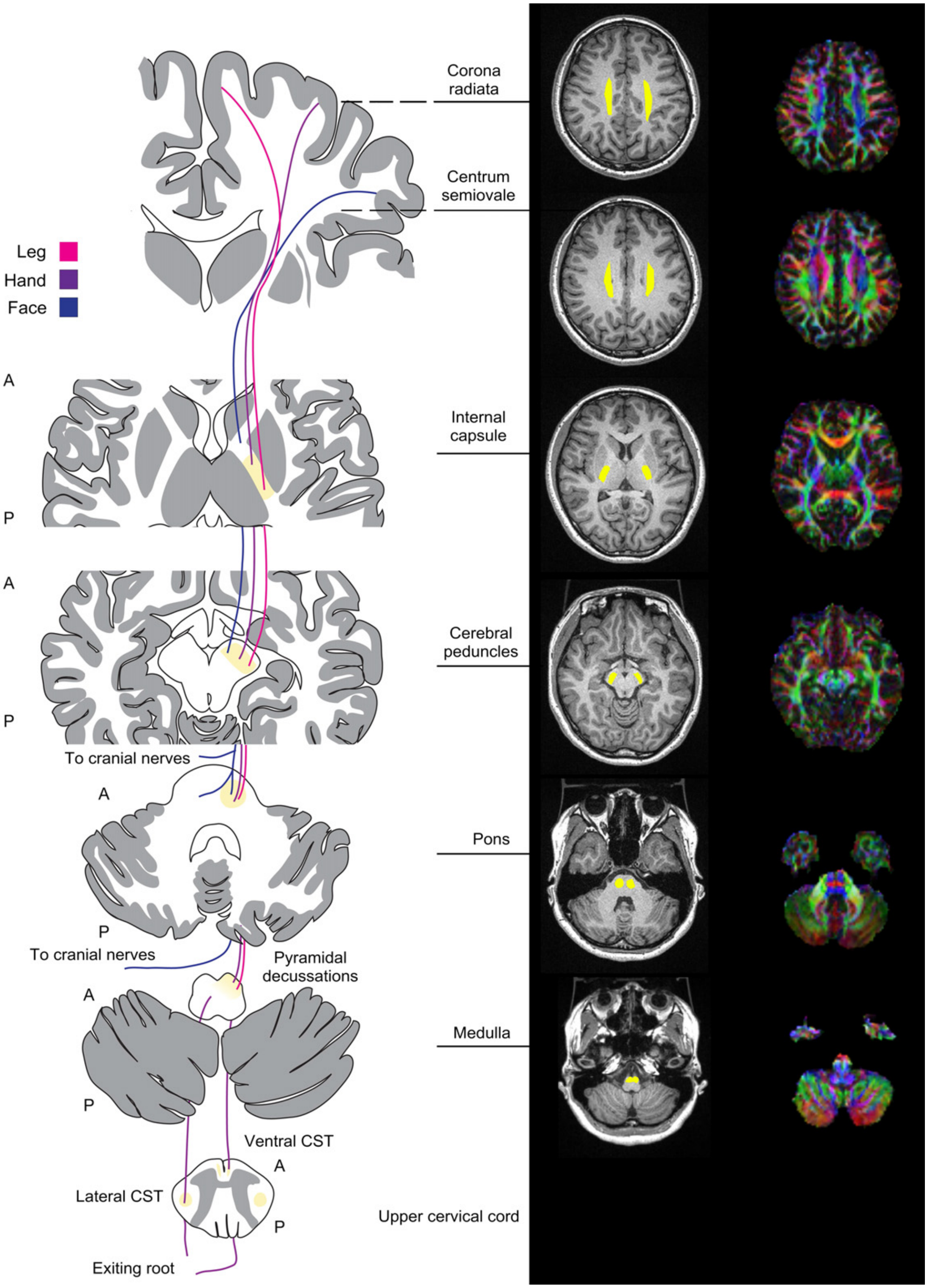

Fig. 3. A schematic representation of the course of the corticospinal tracts at various anatomic levels with corresponding T1-weighted MR image T1 and color FA (cFA) maps. Orientation of schematic illustrations match that of MR image (anterior [A] is the upper margin of each slice and posterior [P] is the lower margin.)

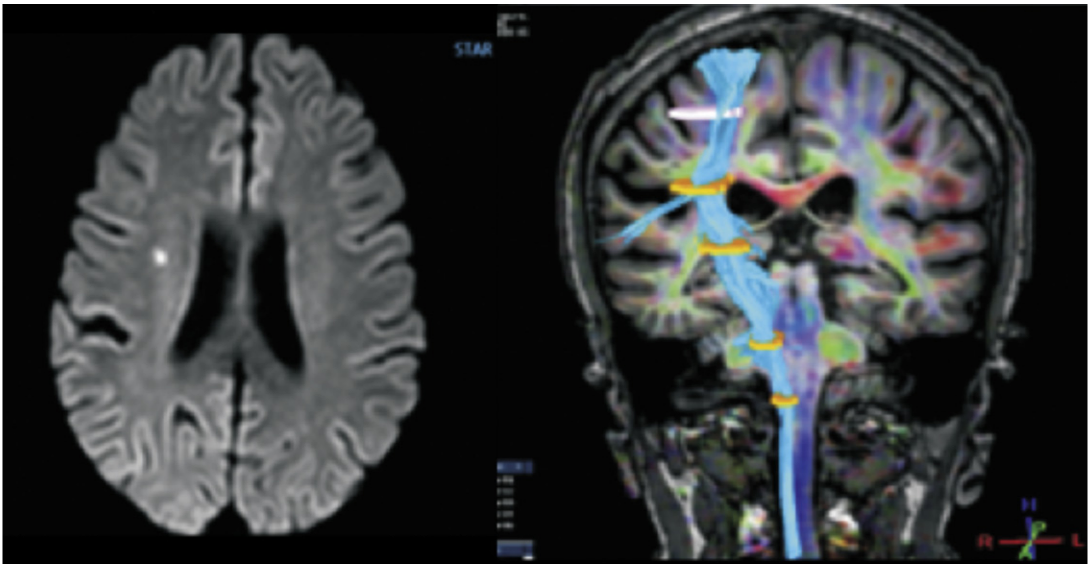

Fig. 4. Uncrossed pyramidal tracts: a previously normal young adult with acute weakness on the right side and focal-diffusion-restricted lesion in the right corticospinal tract. Weakness on the same side was well explained with diffusion tractography (coronal postprocessed tractography superimposed on T1-weighted image), which showed that most of the right-sided fibers were continuing down the same side below the level of the medulla. This patient did not have scoliosis or lateral gaze palsy, a syndrome that has been well described with uncrossed pyramidal tracts. (*Courtesy of* Ashish Atre, MD, STAR Imaging Center, Pune, India).

Corticobulbar Tracts

Corticobulbar tracts connect the motor cortex to cranial nerve nuclei in the brainstem. These fibers pass through the corona radiata and genu of internal capsule to run mediodorsal to the corticospinal tracts at the level of the cerebral peduncles.

Corticopontine Tracts

Corticopontine fibers arise from precentral and postcentral gyri with substantial contributions from premotor, supplementary motor, and posterior parietal cortices as well as from prefrontal and temporal cortices. The fibers course through the anterior limb of the internal capsule and medial cerebral peduncle before projecting into the pontine nuclei. Second-order neurons from the pontine nuclei decussate to the contralateral side and give rise to pontocerebellar pathways.

The corticospinal, corticopontine, and corticobulbar tracts run together and cannot be identified separately from each other using DTI but may be parcellated using advanced color maps.[12]

Internal Capsule

The internal capsule is the main conduit for projection fibers and is divided into 3 main sections. The anterior limb of internal capsule lies between the lentiform nucleus and the head of the caudate nucleus and carries the anterior thalamic radiations and frontopontine tracts. The PLIC separates the posterior aspect of the lentiform nucleus and the thalamus and contains corticospinal, corticobulbar, and frontopontine fibers; the superior thalamic radiation; and a smaller number of fibers connecting to the tectal, rubral, and reticular systems.

The PLIC can be further subdivided into thalamolenticular, sublenticular, and retrolenticular segments. Within the retrolenticular portion of the PLIC runs the posterior thalamic radiation (which includes the optic radiation) and the corticotectal, corticonigral, and corticotegmental fibers. The sublenticular portion of the PLIC contains the inferior thalamic radiation, auditory radiation, and temporal and parieto-occipital corticopontine fibers.[2]

The intervening genu of the internal capsule between the anterior and posterior limb contains corticobulbar and corticoreticular fibers as well as some frontopontine and superior thalamic radiation fibers.

Thalamic Radiations

The thalamus is known to have reciprocal connections (corticothalamic and thalamocortical fibers) to wide areas of the cortex. These fibers pass through the anterior and posterior limbs and retrolenticular segment of the internal capsule as the anterior, superior, and posterior thalamic radiations (**Fig. 5**) and fan out to form the corona radiata.[13]

Reciprocal connections include the *anterior nucleus* and *cingulate* cortex, *ventral lateral nucleus* and *motor* cortex, *ventral anterior nucleus* and *supplementary motor* area, *ventral posterior nucleus* and *sensory* cortex, *lateral geniculate body* (LGB) and *visual* cortex, *medial geniculate* body and *primary auditory* cortex, and *dorsomedial nucleus* and *prefrontal* cortex (**Fig. 6**).

Geniculocalcarine Tract (Optic Radiation)

The geniculocalcarine tract connects the LGB to the primary visual cortex and consists of 3 white matter bundles (**Fig. 7**). The *anterior bundle* corresponds to the lower retina fibers and projects from the LGB to run laterally then anteriorly across the roof of the anterior tip of the ipsilateral temporal horn. This bundle then makes a sharp turn to pass posteriorly forming the Meyer loop (**Fig. 8**) along the inferior lateral wall of the temporal horn through the temporal stem to converge on the lower lip of the calcarine fissure.[4] As it courses along the wall of the temporal horn, the Meyer loop lies deep to the inferior occipitofrontal fasciculus (**Fig. 9**).[4]

The Meyer loop is an important consideration in epilepsy surgery because damage during surgery can result in homonymous upper quadrantanopia. The anterior border of the Meyer loop and its relation to the tip of temporal horn and temporal pole has been a matter of controversy.[12]

Some studies have shown that the anterior extent of the Meyer loop may run more rostral than the tip of the temporal horn and may lie 20 mm from the tip of the temporal lobe.[4] Conversely, more recent studies with DTI have shown that the Meyer loop does not reach as far anteriorly as the tip of the temporal horn. The general consensus at present is that there is likely individual anatomic variation, making it difficult to give a generic recommendation on safe lengths of anterior temporal lobe resection without causing a visual field defect.[12] Because probabilistic tractographic studies are showing great promise in the delineation of the Meyer loop, this additional information could be used in neurosurgical planning to help avoid the risk of visual field defects.[12]

The *central bundle* serves the macular region and passes directly laterally, to cross the roof of the temporal horn before coursing along the lateral wall and roof of the trigone and occipital horn to the occipital pole. The *posterior bundle* corresponds to the superior retina and courses directly posteriorly, over the roof of the trigone and occipital horn, and ends at the upper lip of the calcarine fissure. The lateral walls of the temporal and occipital horns are formed by all the 3 bundles of optic radiation, separated from the ependyma by a thin layer of the corpus callosum, known as the tapetum. In conjunction with the inferior occipitofrontal fasciculus, inferior longitudinal fasciculus, and inferior aspect of the SLF, the optic radiation

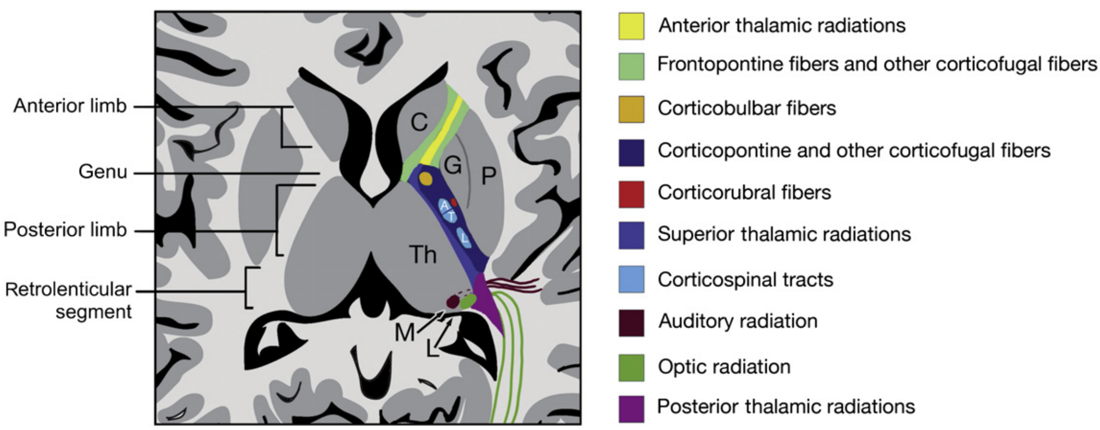

Fig. 5. Simplified illustration of internal capsule and main fiber tracts. Boundaries of the tracts should not be considered as definite because there is no precise distinction between some tracts. The corticospinal tracts are orientated such that the fibers representing arms (A) are anterior to the trunk (T), which in turn are anterior to the fibers representing the limbs (L). The auditory and optic radiations are shown arising, respectively, from the medial (M) and lateral (L) geniculate bodies (*arrows*). The gray matter structures: the caudate (C), globus pallidus (G), putamen (P), and thalamus (Th) are shown bounding the anterior and posterior limbs of the internal capsule.

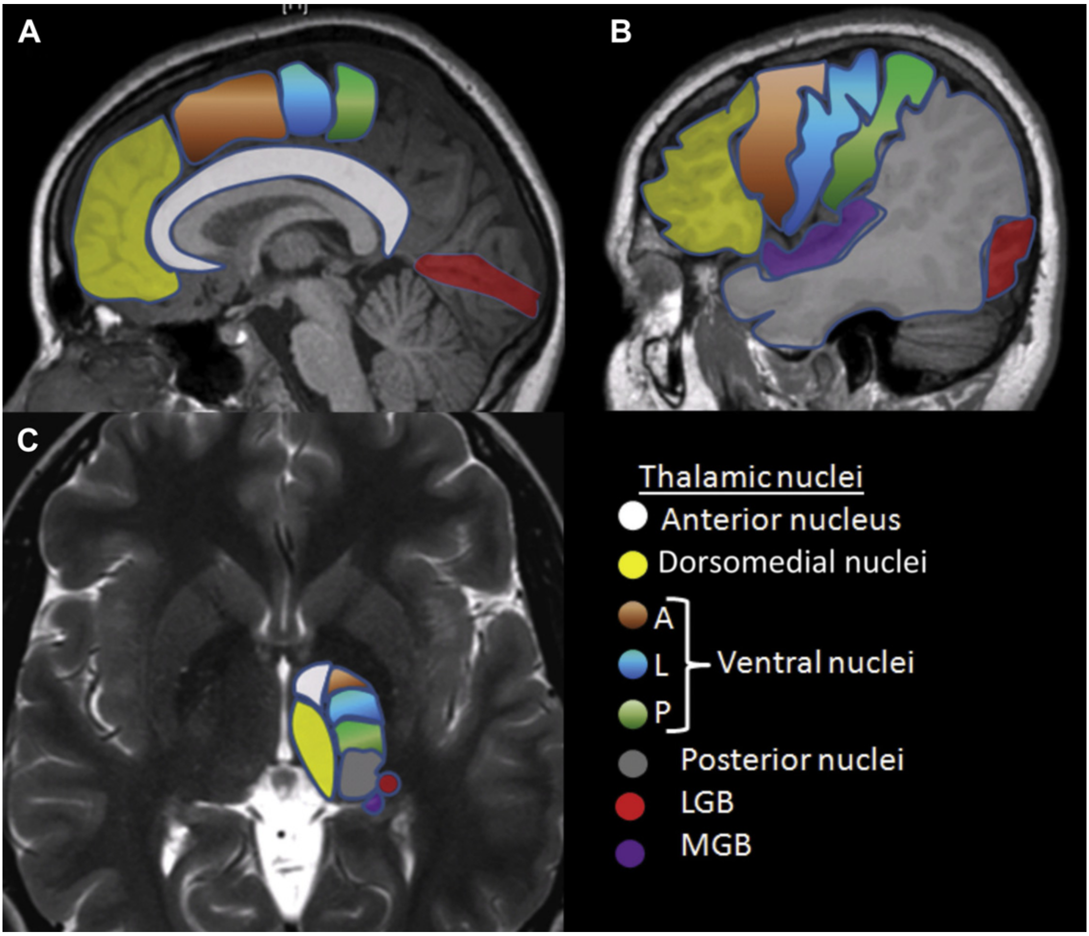

Fig. 6. Simplified illustration of reciprocal connections of thalamic nuclei to the cortical areas. Sagittal T1 midline (*A*), Sagittal T1 through the temporal lobe (*B*), axial T2 through the thalami (*C*). A, L, and P represent anterior, lateral, and posterior ventral nuclei, respectively; LGB, lateral geniculate body; MGB, medial geniculate body.

mingles posteriorly to form much of the sagittal stratum in the occipital lobe.

ASSOCIATION FIBERS

Association fibers unite different cortical areas within the same hemisphere and can be short or long. *Short association fibers* connect areas within the same lobe and include subcortical U fibers, which connect adjacent gyri (**Fig. 10**). The work by Oishi and colleagues[14] on a population-based atlas of the superficial white matter using DTI divides the cortical areas into 9 blade-type structures, further parcellated into 21 subregions. *Long association fibers* identifiable on DTI include the SLF, inferior longitudinal fasciculus, middle longitudinal fasciculus (MLF), uncinate fasciculus, superior fronto-occipital fasciculus, and inferior fronto-occipital fasciculus.

Superior Longitudinal Fasciculus

The SLF is the largest association bundle composed of bidirectional fibers connecting the frontal lobe to the parietal, temporal, and occipital lobes and includes the arcuate fasciculus (**Fig. 11**). Makris and colleagues[15] in their in vivo DTI study demonstrated that the SLF, as it is in primates, can be divided into 4 distinct components: SLF I, SLF II, SLF III, and the arcuate fascicle (AF).

SLF I

SLF I is located in the superior parietal lobe, precentral and postcentral gyri, superior precuneus, and posterior part of the superior frontal gyrus.[15] The medial and superior parietal involvement of SLF I suggests its contribution in regulating higher aspects of motor behavior, including conditional associative tasks (ie, selection of different motor tasks based on conditional rules).

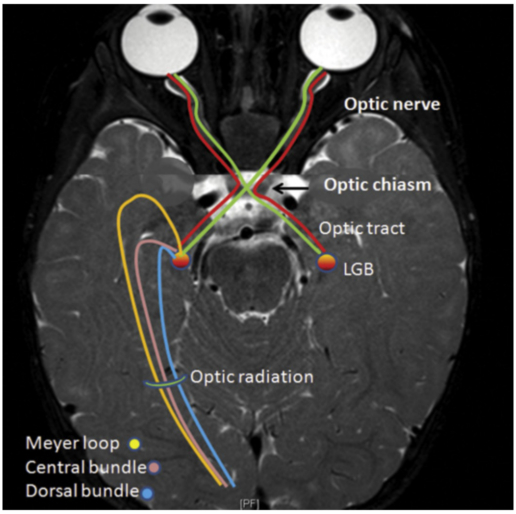

Fig. 7. MR image of visual pathway showing optic nerves, chiasm (*arrow*), optic tracts, lateral geniculate body (LGB), and optic radiations. Anterior, central, and posterior bundles of optic radiation as they course to the occipital cortex are also shown.

SLF II

SLF II connects the prefrontal cortex with the caudal inferior parietal cortex and is located in the angular gyrus, supramarginal gyrus, precentral and postcentral gyrus, middle frontal gyrus, and occipito-temporo-parietal region. SLF II provides bidirectional information and feedback between the prefrontal and posterior parietal regions with information regarding perception of visual space, with lesions resulting in disorders of spatial working memory.

SLF III

SLF III may function to transfer somatosensory information, including language articulation and monitoring orofacial and hand motions. SLF III has possible connections between the pars opercularis and supramarginal gyrus, with bidirectional connections between the ventral prefrontal cortex and inferior parietal lobule.

AF

The AF connects the frontal lobe, supramarginal gyrus, posterior part of the superior temporal gyrus, and temporo-occipital region and can be subdivided into the following segments:

- *Frontotemporal (FT) segment*: connects the inferior frontal cortex (Broca area, in the dominant hemisphere) with the superior temporal cortex (Wernicke area in the dominant hemisphere).
- *Frontoparietal segment*: connecting the inferior frontal cortex and the parietal cortex.
- *Temporoparietal segment*: connecting the temporal cortex in the region of the superior and middle temporal gyri with the parietal cortex.[16] Eluvathingal and colleagues[16]

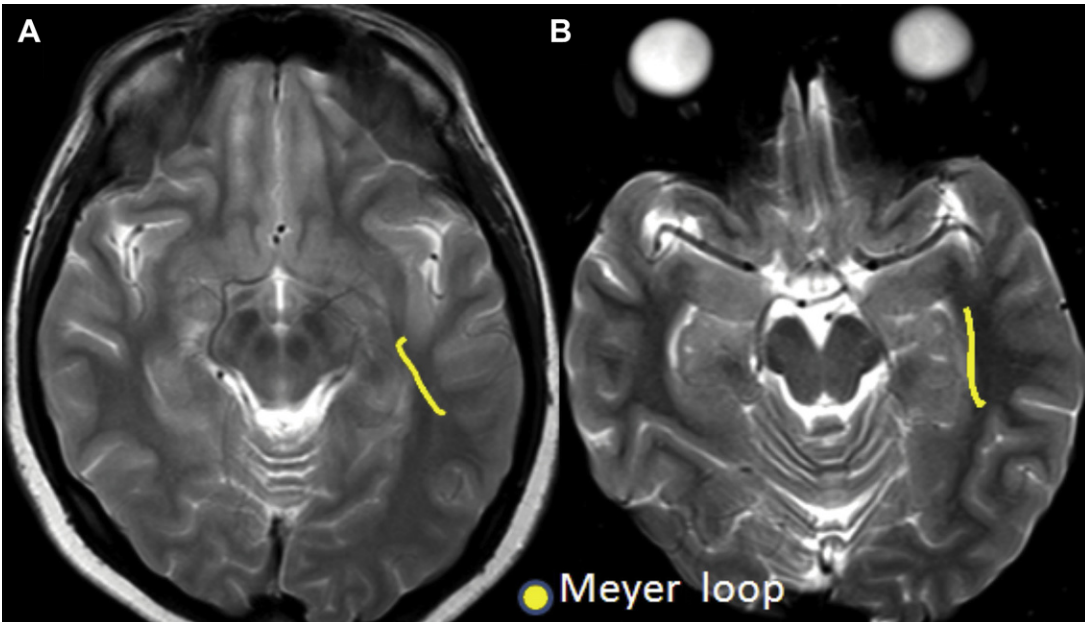

Fig. 8. Axial images of Meyer loop at the lateral geniculate body level (*A*) shows its location along the roof of temporal horn. At the level of hippocampus (*B*), it is seen along the lateral wall of temporal horn. Note that the anterior extent does not reach up to the tip of temporal horn.

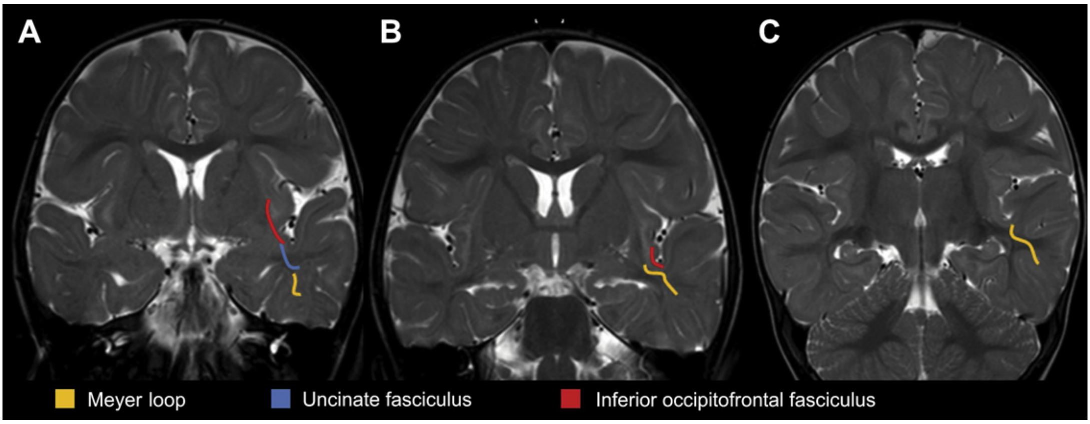

Fig. 9. (*A*) Image at the level of the amygdala (*A*) showing anteriormost segment of the Meyer loop and its relation to the inferior occipitofrontal fasciculus (IOF) and uncinate fasciculus. (*B*) Image at the level of the hippocampus, showing the Meyer loop superolateral to temporal horn and passing through the temporal stem. At this level, the Meyer loop is deep to the IOF. (*C*) Image at the level of the lateral geniculate body shows the Meyer loop, located above and lateral to the temporal horn.

showed that the FT segment of the AF was not visible in 29% of normal cases and that the left FT segment demonstrates higher FA values than the right, consistent with functional and anatomic lateralization of language to the dominant hemisphere.

Interruption or insult to the SLF decreases the ability to repeat spoken language and can also cause unilateral neglect.

Inferior Longitudinal Fasciculus

The inferior longitudinal fasciculus connects the cortices of the anterior temporal and posterior occipital lobe and joins the inferior aspect of the SLF, optic radiations, and inferior longitudinal fasciculus to form the sagittal stratum traversing the occipital lobe (**Figs. 12** and **13**). It has been shown that the inferior longitudinal fasciculus and the inferior fronto-occipital fasciculus share most of the projections from the posterior temporal and occipital lobes.[5] Interruption of this fasciculus may result in unilateral visual neglect, visual amnesia, and hallucinations and also visual hypoemotionality.[17,18]

Middle Longitudinal Fasciculus

Makris and colleagues[19] have delineated the MLF in humans and found it to be similar to the

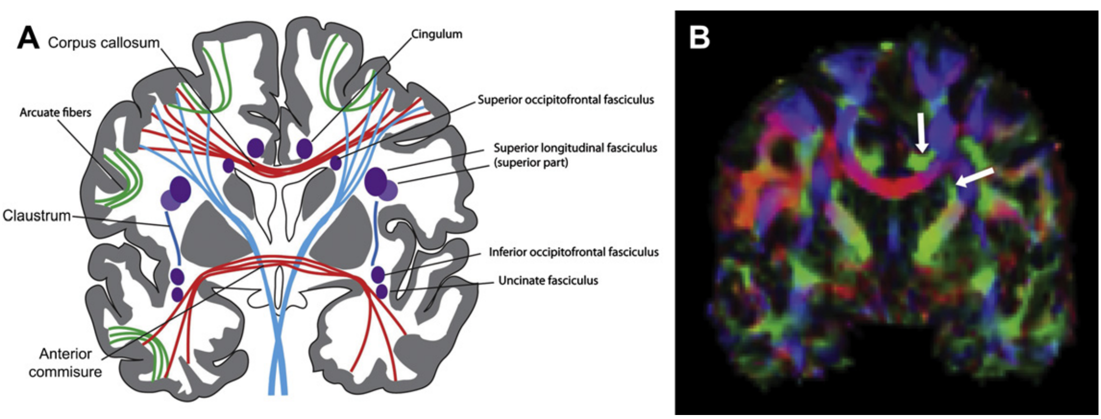

Fig. 10. Coronal illustration showing various association and commissural fibers and their relations. (*A*: Schematic, *B*: coronal color FA map at the level of the frontal horns) The corpus callosum is seen between the cingulum superomedially and the superior occipitofrontal fasciculus inferolaterally (*arrows*). The SLF courses along the superior margin of the claustrum in an arc and is separated from the SLF by internal capsule and corona radiata. The inferior occipitofrontal fasciculus lies along the inferolateral edge of the claustrum along the inferior insula. Uncinate fasciculus is seen inferomedial to the inferior occipitofrontal fasciculus.

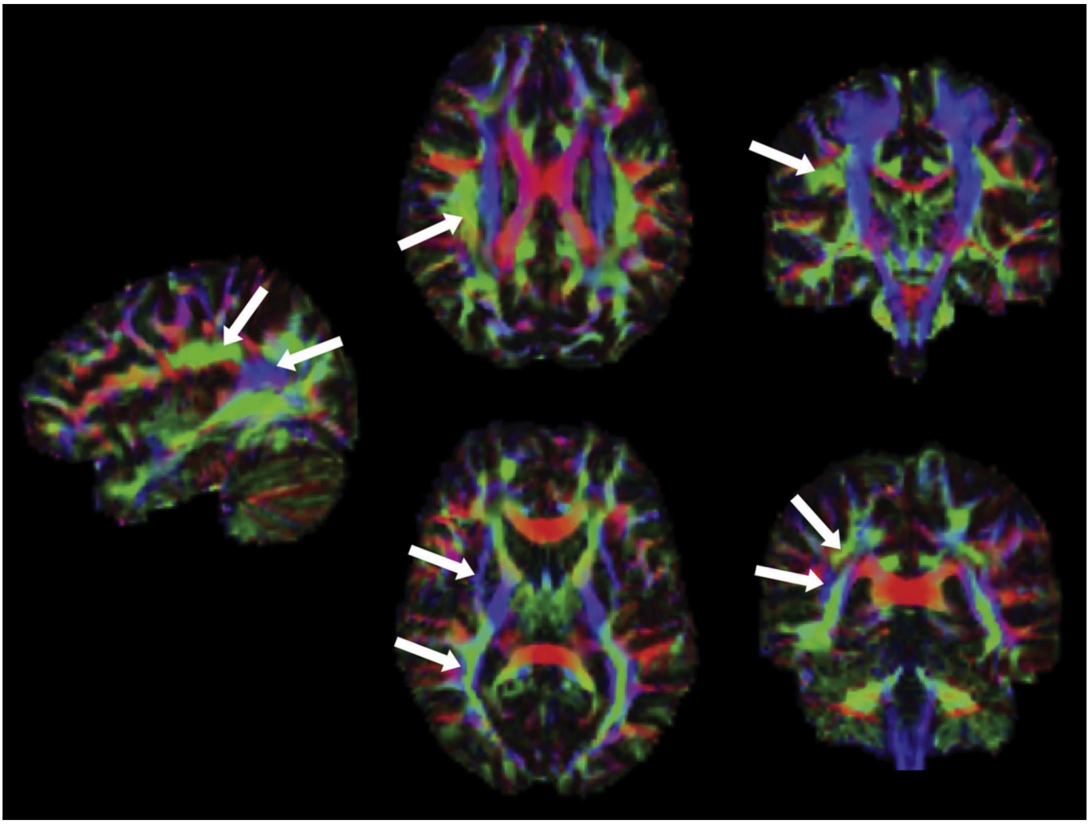

Fig. 11. The course (*arrows*) of the superior longitudinal fasciculus on color FA (cFA) DTI images.

described tracts in rhesus monkeys. The MLF extends from the caudal part of the inferior parietal lobule, specifically the angular gyrus, to the white matter of the superior temporal gyrus, remaining within the white matter of the superior temporal gyrus (**Fig. 14**).

The MLF is distinct from other adjacent fiber tracts such as the SLF II and the AF, which lie more laterally. Because of its location it is suggested that the MLF could have a central role in language (dominant hemisphere) and attention (nondominant hemisphere) functions.

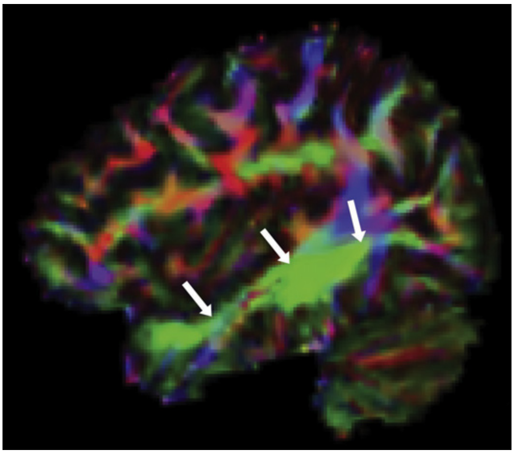

Fig. 12. Sagittal course (*white arrow*) of the inferior longitudinal fasciculus on color FA (cFA) DTI.

Superior Occipitofrontal Fasciculus

The name superior occipitofrontal fasciculus is a misnomer because its fibers actually connect the frontal and parietal lobes (**Fig. 15**),[20] and hence it should probably be named the superior fronto-parietal fasciculus. This fasciculus lies deep to the corpus callosum, extending posteriorly along the dorsal border of caudate nucleus, and runs parallel to the SLF. Anteriorly it lies in the superior edge of the anterior limb of the internal capsule before projecting into the frontal lobe.[19] The functions of this fasciculus include spatial awareness and symmetric processing. A possible link between white matter hyperintensity burden and late life depression has been suggested.[21]

Inferior Occipitofrontal Fasciculus

This fasciculus connects the occipital and frontal lobes and also contains fibers connecting the frontal lobe with the posterior part of the parietal and temporal lobes. Fibers from the lateral frontal

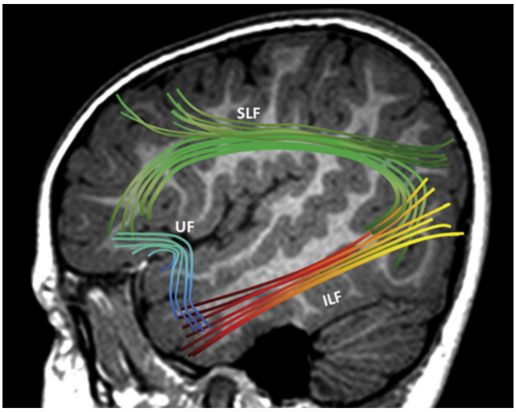

Fig. 13. MR image demonstrating relative trajectories of the SLF, uncinate fasciculus (UF), and inferior longitudinal fasciculus (ILF) to one another.

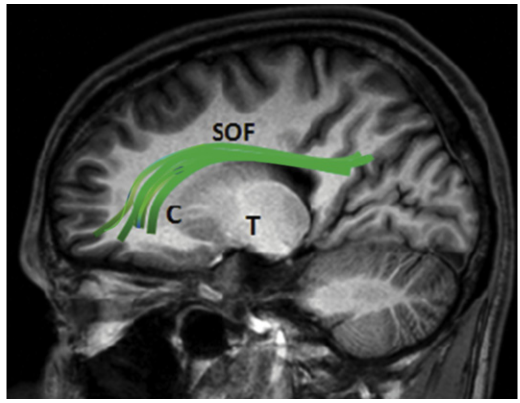

Fig. 15. Illustrating the course of the superior occipitofrontal fasciculus (SOF) arcing over the caudate nucleus and connecting frontal and parietal lobes. C, caudate nucleus; T, thalamus.

lobe converge into a single bundle to run along the inferolateral edge of the lentiform nucleus, at the inferior aspect of the claustrum, and may lie in the external as well as the extreme capsules. This fasciculus runs superior to the uncinate fasciculus in the temporal stem (**Fig. 16**).[4] Posteriorly, the inferior occipitofrontal fasciculus joins the inferior longitudinal fasciculus, the descending portion of the SLF, and portions of the geniculocalcarine tract to form most of the *sagittal stratum*, a large and complex bundle that connects the occipital lobe to the rest of the brain.[3]

This fasciculus may connect more superiorly located regions of the frontal lobe with more posterior areas of the temporal lobe, than those connected by the uncinate fasciculus. The fibers seem to connect auditory areas with visual association cortex in the temporal lobe with prefrontal cortex.[21] Owing to the longer connections of the inferior occipitofrontal fasciculus, it may play a larger role of disease spread between the frontal and temporal lobes than the uncinate fasciculus. This tract may have a role in triggering temporal lobe syndromes in extratemporal lesions as well as be associated with amnesia, schizophrenia, and Alzheimer disease.

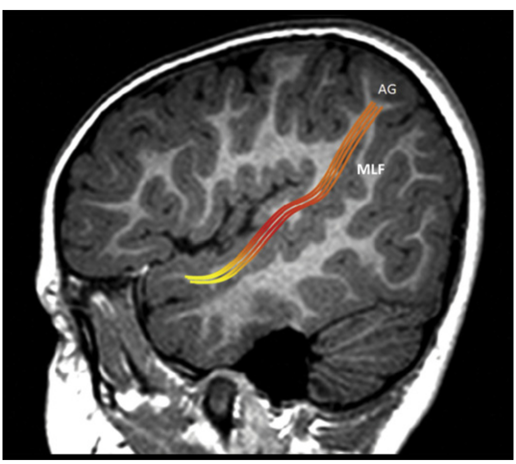

Fig. 14. MR image showing middle longitudinal fasciculus (MLF) extending from inferior parietal lobule to temporal pole. AG, angular gyrus.

Uncinate Fasciculus

The uncinate fasciculus (of Russell) is a hook-shaped bundle of fibers and is also known as the temporofrontal (frontotemporal) fasciculus. This fasciculus connects the orbital and inferior frontal gyri and gyri rectus to the anterior temporal lobe, consisting of both afferent and efferent fibers. The fasciculus can be divided into 3 parts: temporal, insular, and frontal segments. Specifically it connects cortical nuclei of the uncus and amygdala to the subcallosal region and superior, medial, and inferior temporal gyri to the gyrus rectus and medial and lateral orbital gyri. In the temporal stem, the tract lies inferomedial to the inferior occipitofrontal fasciculus. Anteriorly the fibers curve upward behind and over the M1 segment of the middle cerebral artery (**Fig. 17**). The inner fibers pass through the external and extreme capsule, with part of the claustrum embedded in its fibers, before fanning horizontally in the frontal orbital white matter.[4]

The uncinate fasciculus has the longest period of development in terms of FA, and is the only major white fiber track that continues to develop beyond the age of 30 years.[22] In contrast to adults, FA values have not shown any asymmetry in diffusivities between right and left tracts in children.[16]

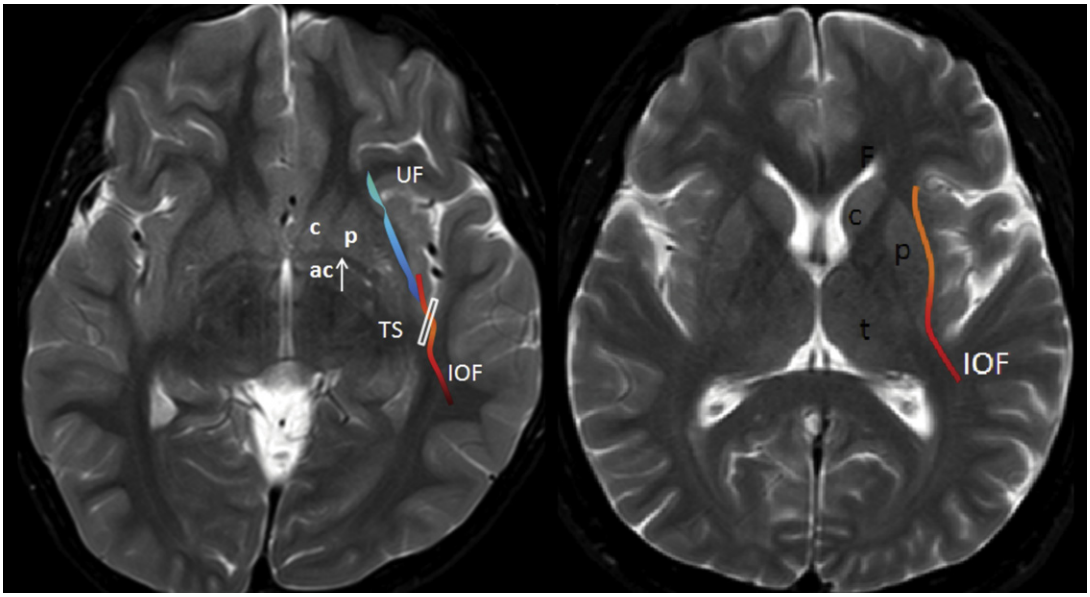

Fig. 16. Axial images showing the relation of uncinate fasciculus (UF) and inferior occipitofrontal fasciculus (IOF). The uncinate fasciculus courses through the anterior-most aspect of temporal stem (TS, shown as *small rectangle*) and the superior extent lies below the level of the frontal horns. IOF courses through the more posterior aspect of temporal stem, traverses its entire extent, and superiorly extends to the level of frontal horn. Uncinate fasciculus is inferior to the IOF and intermingles with it in the insula and frontal pole. C, caudate nucleus head; p, putamen; t, thalamus; ac, anterior commissure (shown with *arrow*); UF, uncinate fasciculus; IOF, inferior occipitofrontal fasciculus.

Traditionally considered to be part of the limbic system, the exact function of the uncinate fasciculus remains unknown. The integrity of the left uncinate fasciculus has been related with proficiency in auditory–verbal memory and declarative memory.[23] Review of many experimental studies supports the role of the uncinate fasciculus as one of the several connections whose disruption results in severe memory impairment, particularly in posttraumatic retrograde amnesia.[4]

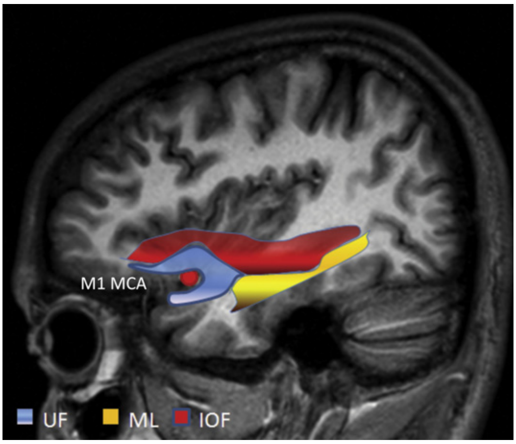

Fig. 17. MR image showing uncinate fasciculus, inferior occipitofrontal fasciculus (IOF), and the Meyer loop fibers projected to the cortical surface. Note the looping of the uncinate fibers around the M1 middle cerebral artery (MCA).

The normal left-greater-than-right asymmetry in the anisotropy in this fasciculus has been shown to be absent in patients with schizophrenia, supporting the theory that patients with schizophrenia have abnormalities of myelin and reduced neuronal integrity of the uncinate fasciculus.[4]

COMMISSURAL FIBERS

Commissural fibers are the white matter tracts connecting corresponding homologous regions between the 2 hemispheres. The main structures discussed are the corpus callosum and anterior commissure.

Corpus Callosum

The corpus callosum is the largest white matter fiber bundle in the brain with more than 300 million axons connecting the corresponding areas of the 2 hemispheres. Although many of these fibers connect homologous/mirror image areas of cortex, there is a significant proportion of asymmetry.

The fibers of the anterior body are transversely oriented. Fibers projecting from the genu and splenium tend to arch more anteriorly and posteriorly, forming the forceps minor and forceps major, respectively. Projections from the splenium, which pass inferiorly along the lateral margin of the posterior horn of the lateral ventricle to the temporal lobes, are called the tapetum and are easily identifiable in midsagittal plane by their right–left orientation (**Fig. 18**). Near the cortex, corpus callosal fibers interdigitate with the association and projection fibers and are difficult to delineate.

The main function of the corpus callosum is interhemispheric sensorimotor and auditory connectivity. Embryologically, the corpus callosum appears at 15 weeks and extends in both anterior and posterior directions during the following weeks, before undergoing more anterior development at 19 weeks.[24] Agenesis may be associated with language delay, language task disconnection, and problems in integrating visual and tactile stimuli. The corpus callosum is specifically involved in multiple sclerosis, lymphoma, and interhemispheric spread of tumor (eg, glioblastoma multiforme).

Anterior Commissure

The anterior commissure is a small compact bundle of fibers between the anterior and posterior columns of the fornix.[25] This commissure contains decussating olfactory fibers connecting the olfactory bulb, anterior olfactory nucleus, and anterior perforated substance, and it also serves to connect the 2 temporal lobes; amygdala; inferior temporal, parahippocampal, and fusiform gyri; and inferior occipital cortex.

OTHER WHITE MATTER STRUCTURES

Temporal Stem

The temporal stem is the white matter bridge between temporal and frontal lobes and extends from the amygdala to the level of the LGB posteriorly (**Fig. 19**). The 3 main tracts passing through the temporal stem are the uncinate fasciculus, inferior occipitofrontal fasciculus, and the Meyer loop of the optic radiations. The temporal stem is an important structure because it is a possible route for tumor, infection, and seizure spread and also plays an important role in numerous disorders, including amnesia, Klüver-Bucy syndrome, traumatic brain injury, and Alzheimer disease (**Fig. 20**).[4] The close proximity of the temporal stem to the insula, basal ganglia, and external and extreme capsule makes it an important landmark during surgery of the temporal lobe.

Limbic System Fibers

Cingulum, fornix, and stria terminalis form the 3 major white matter tracts of the limbic system.

Cingulum

The fibers of the cingulum begin in the parolfactory area below the rostrum of the corpus callosum and arch over the corpus callosum, beneath the length of the cingulate gyrus, to reach the parahippocampal gyrus and uncus (**Fig. 21**). The cingulum carries afferent connections from the cingulate gyrus to

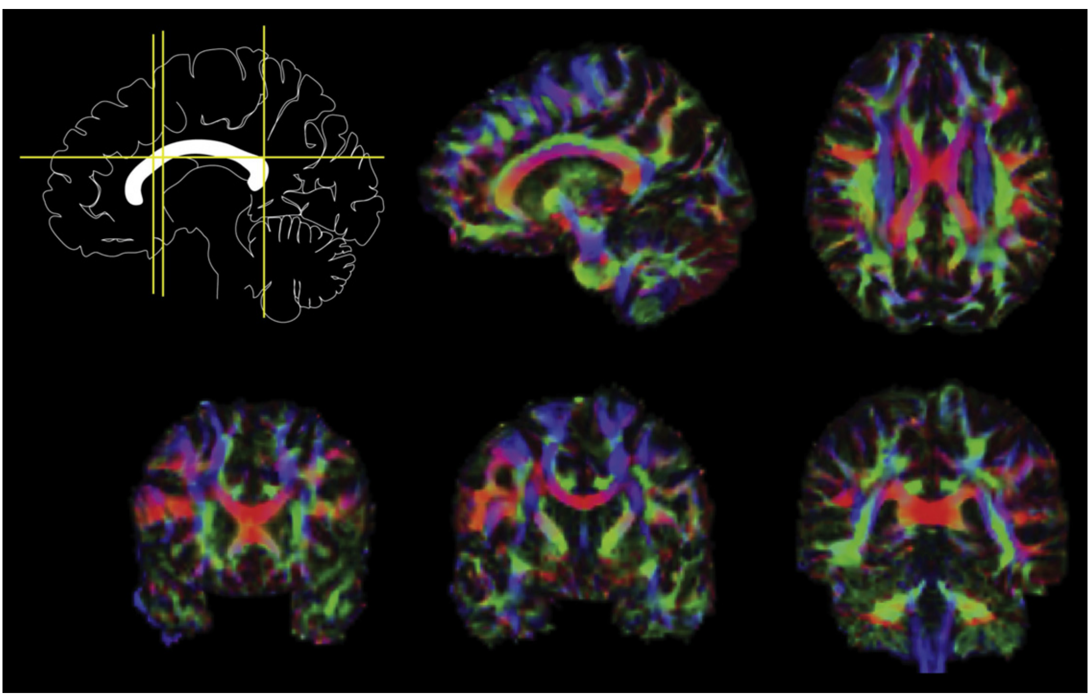

Fig. 18. The corpus callosum and directionality of fibers on color FA (cFA) DTI maps.

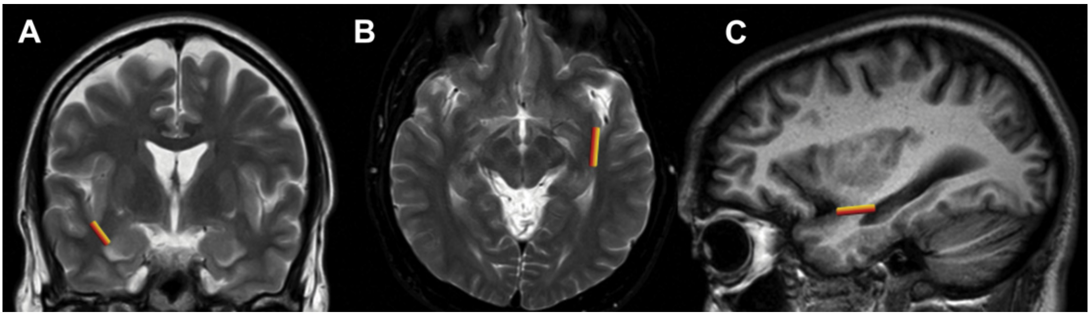

Fig. 19. MR illustration of location of temporal stem on coronal (*A*), axial (*B*), and sagittal (*C*) images.

the entorhinal cortex and connects portions of the frontal, parietal, and temporal lobes. The cingulum becomes appreciable only after 17 weeks' gestation.[24] Functionally the cingulate cortex is subdivided into at least 4 zones with a range of functions including affect, visceromotor and skeletomotor control, visuospatial processing, and memory access.[26]

Fornix

The fornix includes both afferent and efferent pathways between the hippocampus, the septal area (preanterior commissure segment of the fornix), and the hypothalamus and mammillary body (postcommissure). Similar to the cingulum, the fornix has a C-shaped trajectory consisting of the column, body, and crus. The fornix branches into 2 columns near the anterior commissure and projects into the dorsal regions of the hippocampi.

Stria terminalis

The stria terminalis is the innermost C-shaped trajectory of the 3 limbic fibers and provides afferent and efferent pathways between the amygdala and

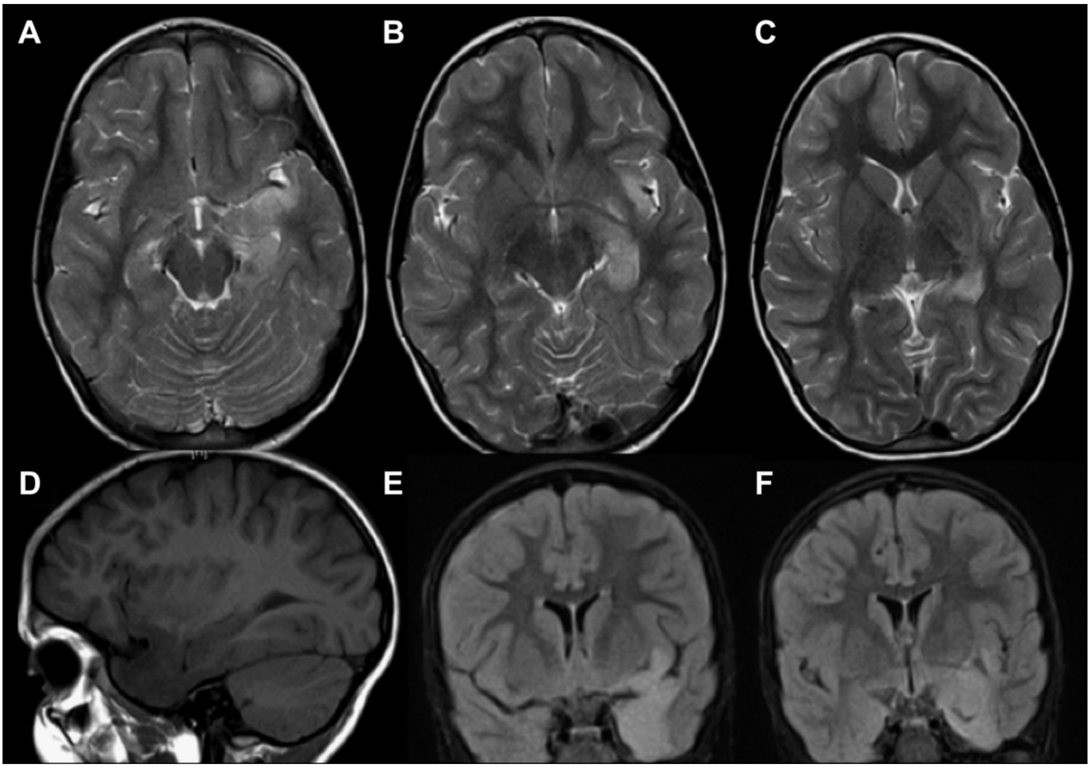

Fig. 20. Axial (*A–C*), sagittal (*D*), and coronal (*E, F*) MR images of left temporal low-grade glioma showing tumor extension through the temporal stem into the region of the external and extreme capsules and inferior frontal region.

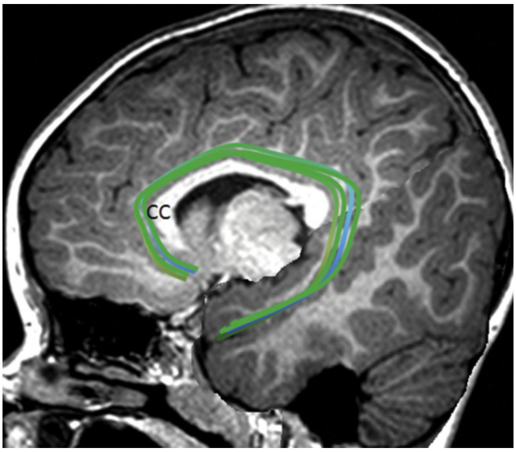

Fig. 21. Trajectory of the cingulum. Note that in this image, a midline image (through the [CC] corpus callosum) and a sagittal image (through the temporal lobe) are superimposed to show the complete trajectory of the cingulum.

the septal area and the hypothalamus. The major role of stria terminalis is in limbic interaction, amygdalar output, and hypothalamic-pituitary-adrenal axis input. Interruption disrupts gonadotropin secretion, and it is a target site for opiate withdrawal therapy. The stria terminalis and fornix are relatively small tracts in adult brains but can be seen as major tracts at 13 weeks' gestation.[24]

BRAINSTEM FIBERS

The 5 major white matter tracts that can be identified within the brainstem on DTI include the superior, middle, and inferior cerebellar peduncles; the corticospinal tract; and the medial lemniscus.[27] The cerebellum is connected to the brainstem by 3 main peduncles. Afferent fibers pass through the inferior cerebellar peduncle and middle cerebellar peduncle (MCP), whereas efferent fibers traverse the inferior and superior cerebellar peduncles.[9] Efferent fibers of the superior cerebellar peduncle originate from the dentate nucleus to connect with the thalamus, red nucleus,

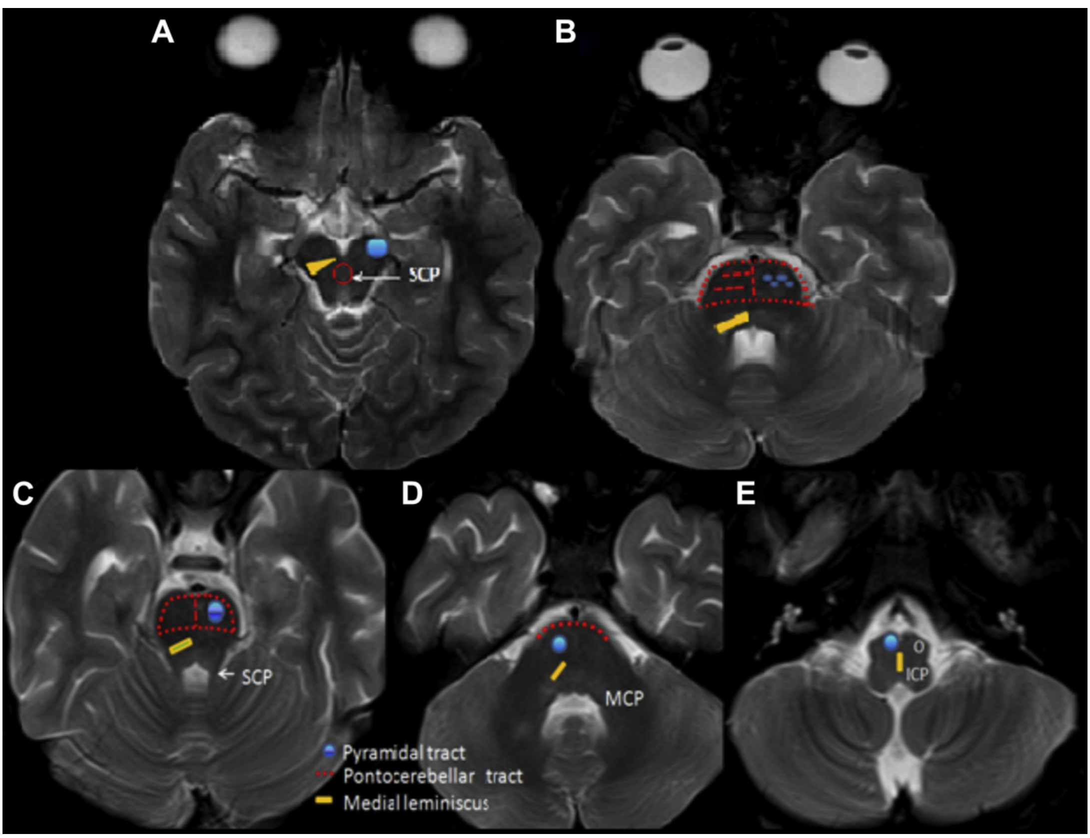

Fig. 22. MR illustration of brainstem tracts. (*A*) Decussation of SCP (*arrow*) at inferior colliculus level. (*B*) Pyramidal tracts being split by the transverse pontine fibers. Level of SCP (*C*), MCP (*D*), and ICP (*E*) showing topography and relations of various tracts. ICP, inferior cerebellar peduncle; O, olive; SCP, superior cerebellar peduncle.

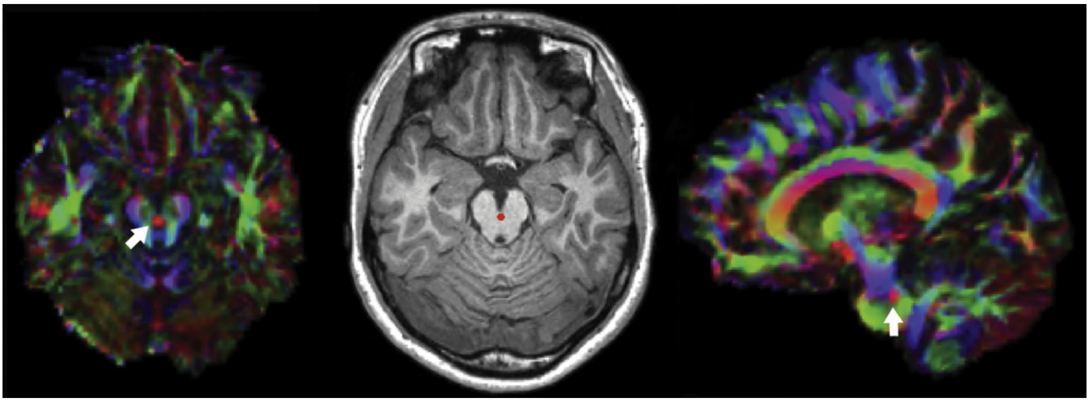

Fig. 23. "Focal red spot" (*arrow*) of the superior cerebellar peduncles' decussation at the level of the midbrain.

vestibular nuclei, and reticular formation. On axial DTI images, the superior cerebellar peduncle is identified at the dentate nucleus level, with a linear green/blue-colored course (**Figs. 22** and **23**). More superiorly, there is a "focal red spot," which is believed to represent the decussation of the superior cerebellar peduncle fibers. Merlini and colleagues[27] found that this decussation may also represent the ventral tegmental decussation.

The superior cerebellar peduncle functions as part of the motor coordination and balance network. Lesions can cause ipsilateral limb and trunk dystaxia. This peduncle is found to be atrophic in progressive supranuclear palsy, and there is an absence of normal decussation of fibers in Joubert syndrome.[21]

The fibers of the MCP are part of the pontocerebellar tracts and form "sheet-like" projections wrapping around the pons with dorsal anterioposterior (green) and ventral left–right (red) directionality. The transverse pontine fibers (red) are also part of the MCP and are seen anteriorly and dorsally to the vertically oriented (blue) corticospinal tracts (**Fig. 24**).[27] These afferent fibers connect the contralateral pontine nuclei to the cerebellum and transmit impulses from the cerebral cortex to the intermediate and lateral zones of the cerebellum.[9] These fibers are involved in initiation, planning, and timing of volitional motor activity and have input from vestibular receptors, thus playing a role in posture, balance, and coordination. Lesions involving the MCP result in ipsilateral limb and gait ataxia.[21]

The *inferior cerebellar peduncle* carries both afferent and efferent fibers and connects the cerebellum and the medulla. Connections include the dorsal spinocerebellar tract and cuneocerebellar, olivocerebellar, vestibulocerebellar, reticulocerebellar, trigeminocerebellar, fastigiobulbar and cerebelloreticular tracts.[9] This peduncle can be

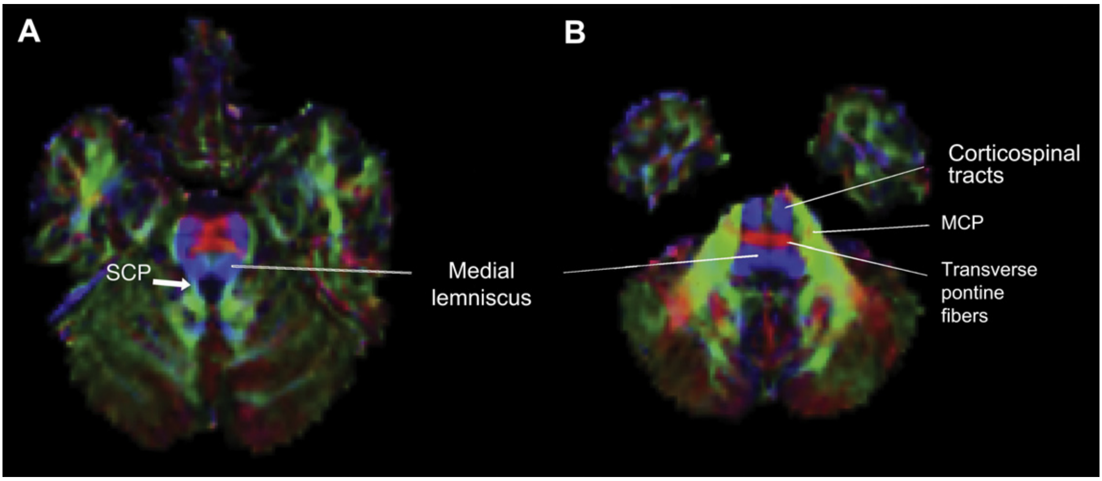

Fig. 24. Color FA (cFA) DTI maps at the level of the (*A*) superior cerebellar peduncle (SCP) (*arrow*) and (*B*) middle cerebellar peduncles (MCPs) demonstrating the position of the corticospinal tracts, transverse pontine fibers of the MCP, and the medial lemniscus.

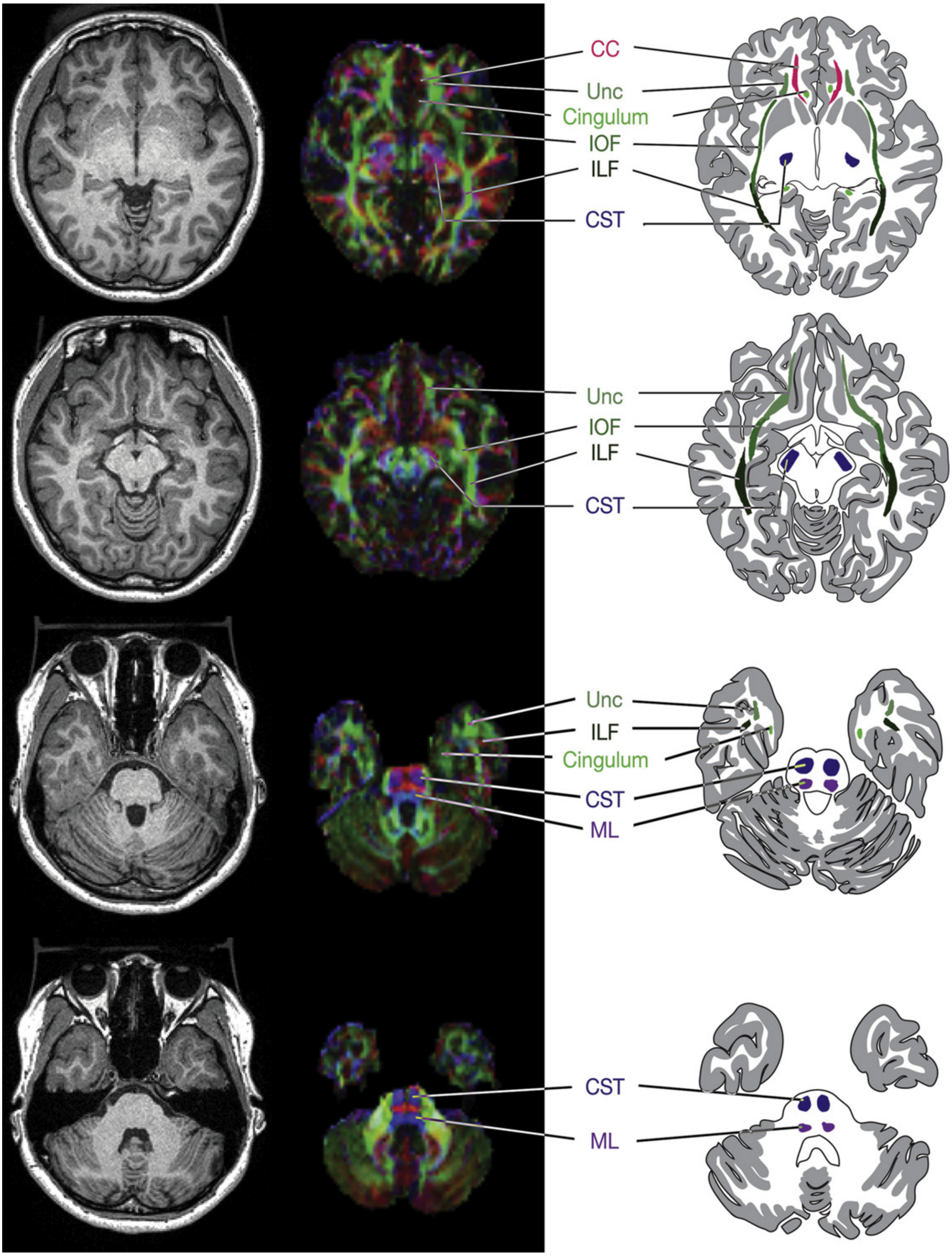

Fig. 25. A summary table of anatomic T1 MR images (first column) with corresponding color-coded FA maps (second column) and line diagrams (third column) depicting the major tracts is provided for quick reference. CC, corpus callosum; CST, corticospinal tract; ILF, inferior longitudinal fasciculus; IOF, inferior occipitofrontal fasciculus; ML, medial lemniscus; SOF, superior occipitofrontal fasciculus; Unc, uncinate fasciculus.

identified along the dorsal aspect of the medulla and pons and is represented by the color blue (inferior-superior direction) in its inferior half and by green in its superior half.[27]

The *medial lemniscus* serves as an important pathway for ascending sensory fibers to the ventroposterolateral thalamus and decussates at the level of the ventral medulla, becoming markedly dispersed at the midbrain level and thus limiting its identification on DTI. The medial lemniscus is best seen dorsal to the dorsal transverse pontine fibers at the level of the MCP[27] and functions to convey sensations of touch, vibration, proprioception, and 2-point discrimination.[21]

SUMMARY

DTI has emerged as an excellent tool for in vivo demonstration of white matter microstructure and has revolutionized our understanding of the same.

Information on normal connectivity and relations of different white matter networks and their role in different disease conditions is still evolving. Evidence is mounting on causal relations of abnormal white matter microstructure and connectivity in a wide range of pediatric neurocognitive and white matter diseases.

Hence there is a pressing need for every neuroradiologist to acquire a strong basic knowledge of white matter anatomy and to make an effort to apply this knowledge in routine reporting, along with being updated in this evolving field. A summary table of color-coded FA maps with corresponding anatomic T1 MR images and line diagrams depicting the major tracts is provided for quick reference of the reader (**Fig. 25**).

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