What Is So Hard about Connectional Neuroanatomy? The Easy Learning “Tract” via Diffusion-Tensor Imaging and Tractography

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Background

Diffusion tensor imaging (DTI) is an advanced form of diffusion weighted imaging in magnetic resonance imaging with useful clinical applications. However, understanding DTI can be challenging, since the technology is dependent on highly complex mathematics and physics. Learning the basic concepts of tensor analysis is key to interpreting DTI and tractography.

Diffusion imaging is based on the inherently random motion of water molecules known as Brownian motion. DTI exploits Brownian motion of water molecules in tissues allowing characterization of molecular diffusion in three dimensions of space.

Diffusion anisotropy effects can be fully characterized and utilized to provide exquisite detail on tissue microstructure. The two most common scalar metrics are fractional anisotropy (FA) and mean diffusivity (MD), which are used to generate images of the diffusion data.

Tractography can also be performed using data from diffusion tensor imaging to allow the mapping of the white matter fiber tracts in the brain.

Diffusion is predominantly anisotropic in the white matter fiber tracts. The direction of maximum diffusivity coincides with fiber tract orientation and is contained within a 3 x 3 matrix of diffusivity measurements known as a diffusion tensor, which can be graphically depicted as an ellipsoid. The ellipsoid is characterized by an eigenvector and its eigenvalues.

Eigenvectors (v) – direction of the ellipsoid (orientation)

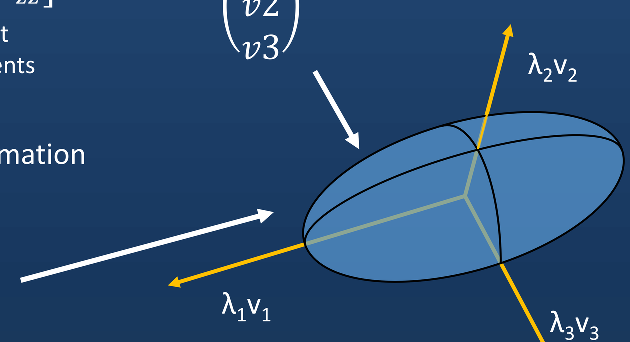
Eigenvalues (λ) – shape of the ellipsoid (diffusivities)

$$\begin{bmatrix} ADC_{xx} & ADC_{xy} & ADC_{xz} \\ ADC_{yx} & ADC_{yy} & ADC_{yz} \\ ADC_{zx} & ADC_{zy} & ADC_{zz} \end{bmatrix}$$

complex 9 non-zero element matrix with 6 distinct elements

eigenvectors $\begin{pmatrix} v1 \\ v2 \\ v3 \end{pmatrix}$

Transformation



$$\begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix}$$

simple matrix with 3 nonzero diagonal elements, **eigenvalues**

The transformation is a change of frame of reference relative to MR scanner to the local of region of interest. The mathematical equivalence of the transformation is ‘diagonalization’ of the diffusion tensor. This operation simplifies the matrix representation of diffusion tensor as shown above. Scalar (invariant) diffusion metrics can be calculated from the eigenvalues. Fractional Anisotropy (FA) reflects the anisotropic fraction of the magnitude of the diffusion tensor. FA varies between 0 (isotropic diffusion) and 1 (infinite anisotropy). The degree of brightness indicates the degree of anisotropy on a gray scale FA map. Alternatively, a color scale can be used to represent the degree of anisotropy.

Fractional Anistrophy

$$FA = \sqrt{\frac{3}{2}}\frac{\sqrt{(\lambda_1-\bar{\lambda})+(\lambda_2-\bar{\lambda})^2+(\lambda_3-\bar{\lambda})^3}}{\sqrt{\lambda_1{}^2+\lambda_2{}^2+\lambda_3{}^2}}$$

with the trace $\bar{\lambda} = \frac{\lambda_1+\lambda_2+\lambda_3}{3}$

Volume Ratio

$$VR = \frac{\lambda_1\lambda_2\lambda_3}{(\bar{\lambda})^3}$$

Median Diffusivity

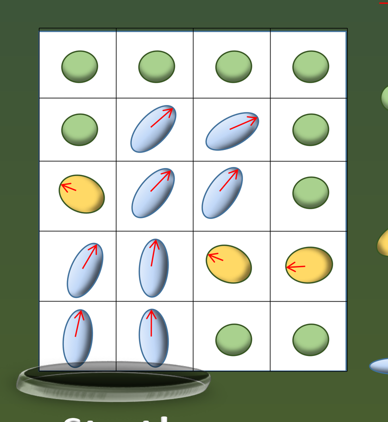
$$MD = \frac{\lambda_1+\lambda_2+\lambda_3}{3}$$

Relative Anisotropy

$$RA = \frac{\sqrt{(\lambda_1-\bar{\lambda})+(\lambda_2-\bar{\lambda})^2+(\lambda_3-\bar{\lambda})^3}}{\sqrt{3}\bar{\lambda}}$$

Tractography

Tractography uses various mathematical algorithms to bidirectionally track the course of white matter fiber tracts passing through a selected region of interest. The most commonly used tracking algorithm follows the principle directions of diffusion (the principle eigenvectors) of adjacent voxels (tensors) so long as the fractional anisotropy is above a set threshold and the principle direction of diffusion is within a given range (cone of probability).



The squares are 2-D representations of voxels within a given plane.

The red arrows represent the principle eigenvector, the primary direction of diffusion for each tensor.

The green spheres represent isotropic tensors which by definition have no principle eigenvector and are below the threshold of fractional anisotropy. They terminate the tracking algorithm.

The yellow ellipsoids represent tensors with fractional anisotropy below threshold and primary direction of diffusion beyond the acceptable range of angular variance. They also terminate the tracking algorithm.

The blue ellipsoids represent tensors with fractional anisotropy and direction within the given thresholds described above.

The translucent disc represents a region of interest, the starting point at which the algorithm begins tracking the principle direction of diffusion from voxel to voxel.

Brain Anatomy and Connectivity

The 3 descriptive neuroanatomical classifications:

SURFACE ANATOMY (IMAGE A)

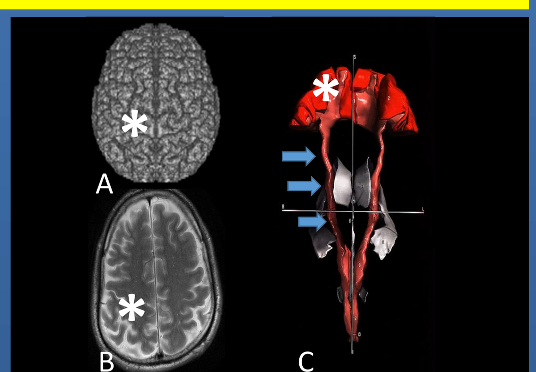
Describes the appearance and topographic organization of gyral convolutions and the interposed sulci.

SECTIONAL ANATOMY (IMAGE B)

Describes the spatial organization of superficial (e.g. cortex), subcortical and deep (e.g. basal ganglia) structures conventionally within orthogonal planes.

CONNECTIONAL ANATOMY (IMAGE C)

Describes the course from start to finish of connecting pathways.

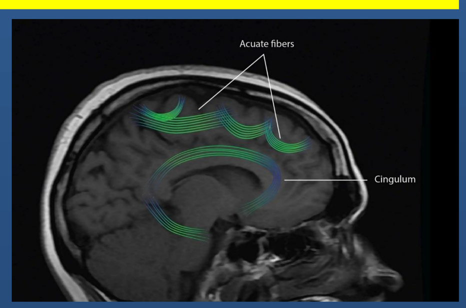


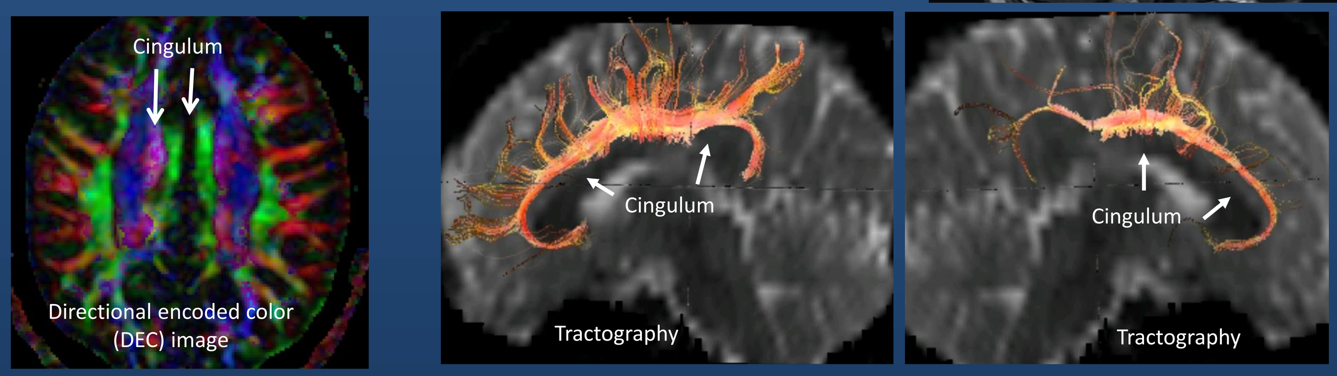
Right-sided central sulcus and perirolandic primary motor and sensory gyri denoted by asterisk (*). Corticospinal tract denoted by arrows.

Association Fibers

Cingulum

The cingulum begins in the parolfactory area of the cortex below the rostrum of the corpus callosum, then courses within the cingulate gyrus, and, arching around the entire corpus callosum, extends forward into the parahippocampal gyrus and uncus.





Uncinate Fasciculus

From the Latin uncus meaning “hook”, hooking around the lateral fissure to connect the orbital and inferior frontal gyri to the anterior temporal lobe.

Anteriorly parallels and lies inferomedial to the inferior occipitofrontal fasciculus. Mid portion adjoins middle part of inferior occipitofrontal fasciculus before heading inferolaterally into anterior temporal lobe

Inferior Occipitofrontal Fasciculus

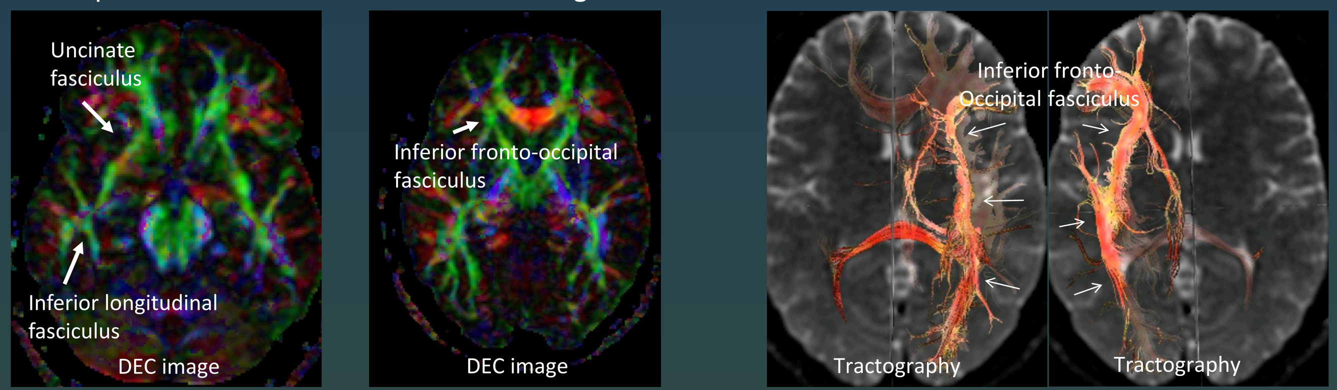
The inferior occipitofrontal fasciculus connects the occipital and frontal lobes but is far inferior compared with the superior occipitofrontal fasciculus.

It extends below the insula. Posteriorly, the inferior occipitofrontal fasciculus joins the inferior longitudinal fasciculus, the descending portion of the superior longitudinal fasciculus, and portions of the optic radiation tract to form most of the sagittal stratum, a large and complex bundle that connects the occipital lobe to the rest of the brain

Inferior Longitudinal Fasciculus

This fiber tract connects temporal and occipital lobe cortices. This tract traverses the length of the temporal lobe

It joins with the inferior occipitofrontal fasciculus, the inferior aspect of the superior longitudinal fasciculus, and the optic radiations to form much of the sagittal stratum



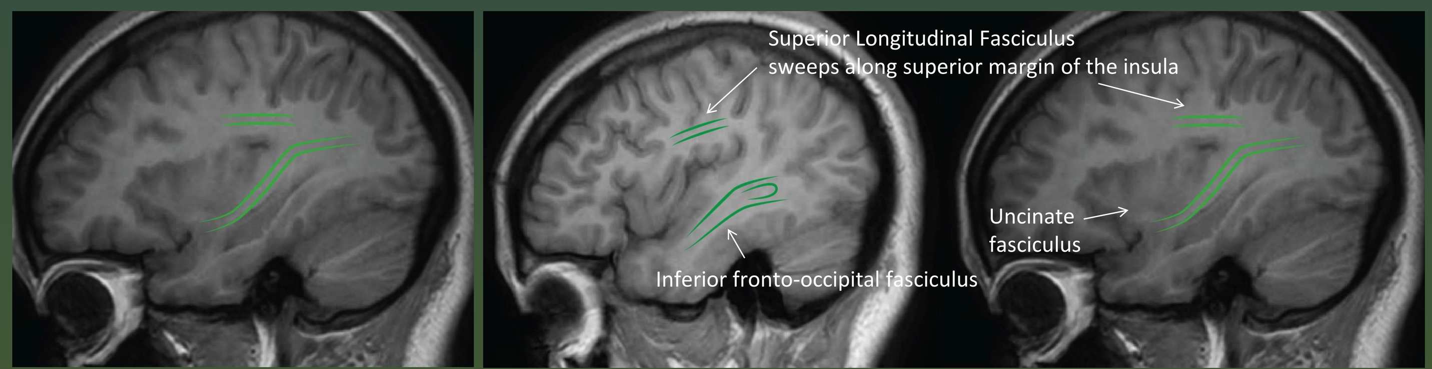
Superior Longitudinal Fasciculus

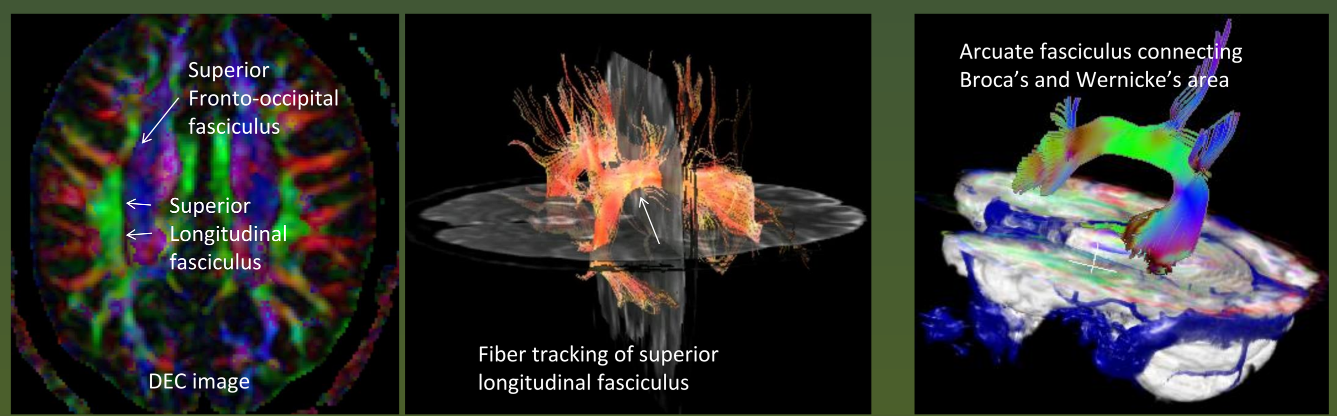
This tract sweeps along the superior margin of the insula in a great arc, gathering and shedding fibers along the way to connect frontal lobe cortex to parietal, temporal, and occipital lobe cortices. The superior longitudinal fasciculus is the largest association bundle

Superior Occipitofrontal Fasciculus

The superior occipitofrontal fasciculus lies beneath the cingulum. It connects occipital and frontal lobes, extending posteriorly along the dorsal border of the caudate nucleus

Portions of the superior occipitofrontal fasciculus parallel the superior longitudinal fasciculus but they are separated from the superior longitudinal fasciculus by the corona radiata and internal capsule





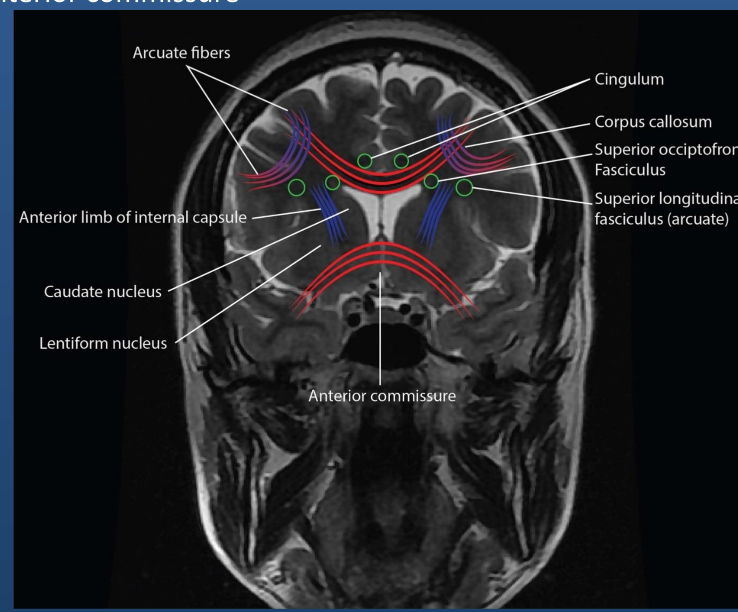
Connectional Neuroanatomy

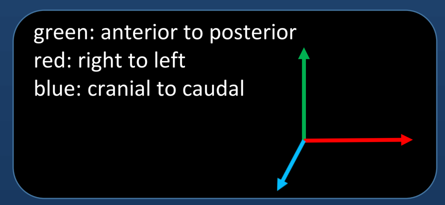
The fiber tracts have been classified into 3 groups based on the general course of the fiber tracts:

Association fibers interconnect cortical areas in each hemisphere. These fibers include cingulum, superior and inferior occipitofrontal fasciculi, uncinate fasciculus, superior longitudinal fasciculus, and inferior longitudinal fasciculus.

Projection fibers interconnect cortical areas with deep nuclei, brain stem, cerebellum, and spinal cord. There are both efferent and afferent fibers. Projection fibers include the corticospinal, corticobulbar, and corticopontine tracts, as well as the optic radiations

Commissural fibers interconnect similar cortical areas between opposite hemispheres. Fibers of the corpus callosum and anterior commissure





Note: Use of the different colors is not arbitrary and denotes direction!

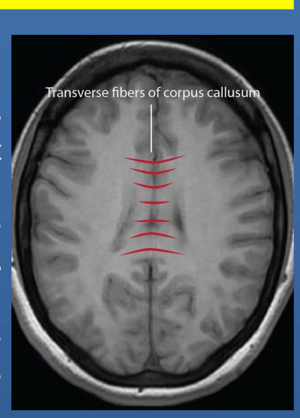
Commissural Fibers

Corpus Callosum

The largest white matter fiber bundle

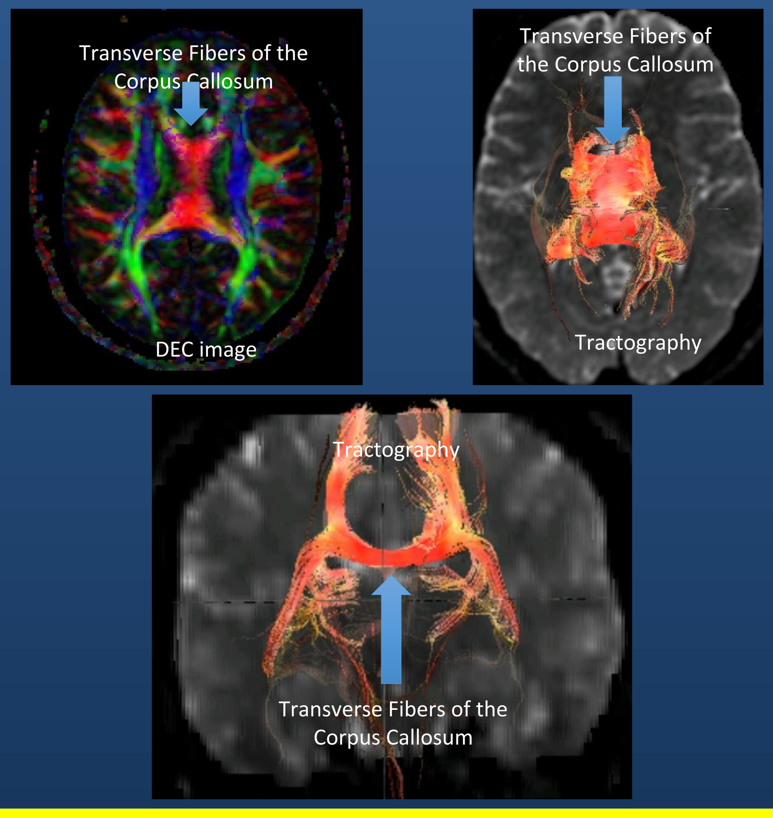
The corpus callosum consists of fibers connecting corresponding areas of cortex between the hemispheres.

Fibers traversing the callosal body are transversely oriented, whereas the fibers traversing the genu and splenium arch anteriorly and posteriorly to reach the anterior and posterior poles of the hemispheres



Anterior Commissure

The anterior commissure crosses through the lamina terminalis. Its anterior fibers connect the olfactory bulbs and nuclei. The posterior fibers connect middle and inferior temporal gyri



Projection Fibers

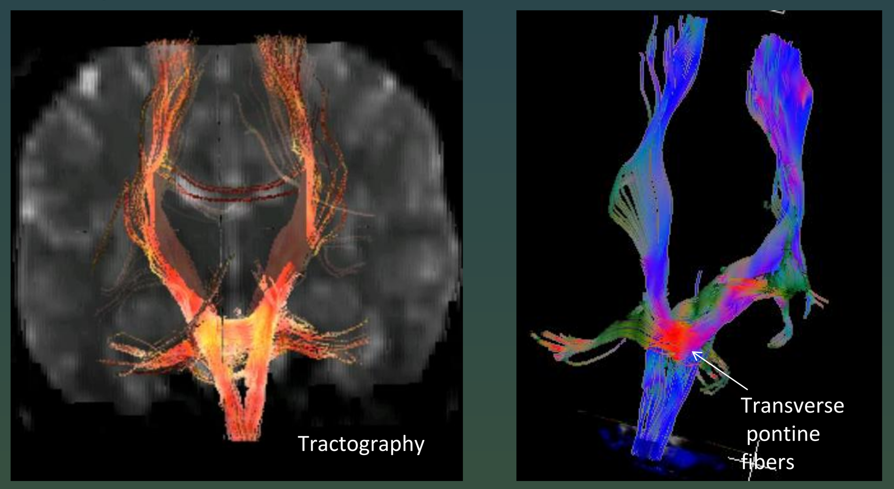
Corticospinal, Corticopontine, & Corticobulbar Tracts

The corticospinal, corticobulbar and corticopontine tracts are major efferent projection fibers that connect motor cortex to the brain stem and spinal cord.

Corticospinal fibers converge into the corona radiate and continue through the **posterior limb** of the internal capsule to the cerebral peduncle on their way to the lateral funiculus.

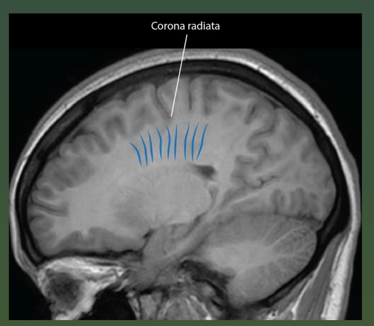
Corticobulbar fibers converge into the corona radiata and continue through the **genu** of the internal capsule to the cerebral peduncle where they lie medial and dorsal to the corticospinal fibers. Corticobulbar fibers predominantly terminate at the cranial motor nuclei

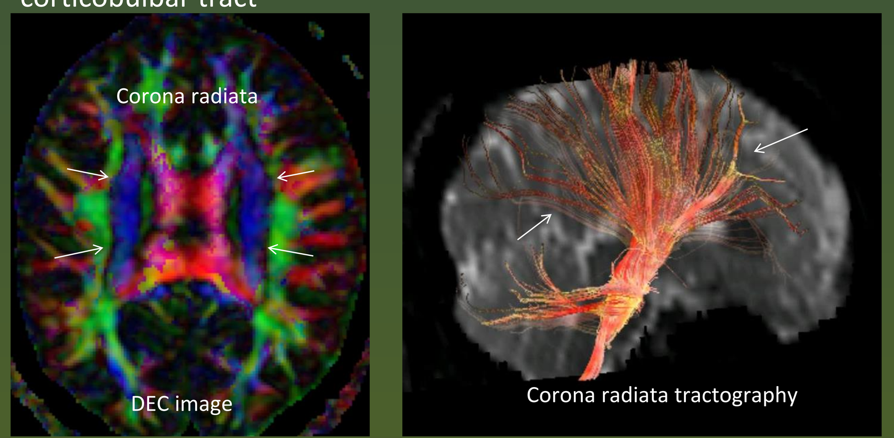
Corticopontine fibers converge into the corona radiata and travel along side the corticospinal fibers. The tract is named according the origination: frontopontine, parietopontine, temporopontine or occipitopontine tract. These fibers terminate at the cranial nuclei in the pons



Corona Radiata

A white matter sheet that continues ventrally as the internal capsule and dorsally as the centrum semiovale. It contains both descending and ascending axons that carry nearly all of the neural signals from and to the cerebral cortex. The corona radiata is associated with the corticospinal tract, the corticopontine tract, and the corticobulbar tract



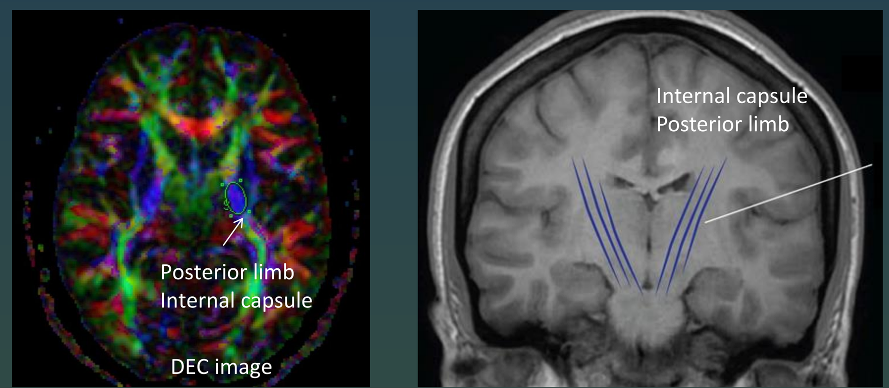


Internal Capsule

A large and compact fiber bundle that serves as a major conduit of fibers to and from the cerebral cortex and is readily identified on directional DTI color maps.

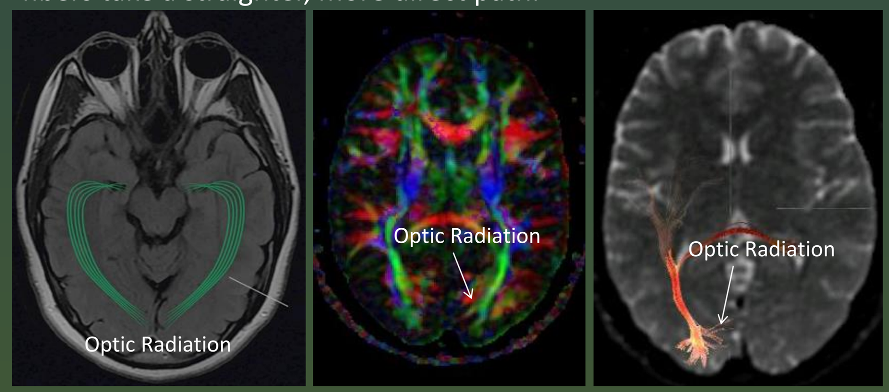
The anterior limb lies between the head of the caudate and the rostral aspect of the lentiform nucleus. The anterior limb passes projection fibers to and from the thalamus (thalamocortical projections) as well as frontopontine tracts, all of which are primarily anteroposteriorly oriented

The posterior limb lies between the thalamus the posterior aspect of the lentiform nucleus. The fibers are the superior-inferiorly oriented fibers of the corticospinal, corticobulbar, and corticopontine tracts



Optic Radiation

The optic radiation connects the lateral geniculate nucleus to occipital (primary visual) cortex. The more inferior fibers of the optic radiation sweep around the posterior horns of the lateral ventricles and terminate in the calcarine cortex; the more superior fibers take a straighter, more direct path.



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