Chapter 2
Human Brain Anatomy in 3D

Wieslaw L. Nowinski

2.1 Introduction

The animal central nervous system (CNS) has been evolved over the last 600 million years, and the human CNS is the most complex living organ in the known universe. The CNS has been extensively investigated, particularly over a few last centuries, and a vast body of materials, resources, and data have been gathered in the print form and more recently also in electronic format. Neuroanatomy is presented in numerous textbooks [1–22], print brain atlases [23–51], and electronic brain atlases [52–74]. Several textbooks combine text with atlases [14, 15, 43, 44], and some provide neuroanatomy for various specialties including neurosurgery [1, 19, 22], neuroradiology [8, 17, 20], neurology [2], and neuroscience [18].

The comprehension of neuroanatomy is crucial in any neurosurgical, neuroradiological, neuro-oncological, or neurological procedure. Therefore, CNS anatomy has been intensively studied by generations of neuroanatomists, neuroscientists, neurosurgeons, neurologists, neuroradiologists, neurobiologists, psychologists, and psychologists, among others, including Renaissance artists. These efforts resulted, however, in neuroanatomy discrepancies, inconsistencies, and even controversies among various communities in terms of parcellation (subdivision), demarcation, grouping, terminology, and presentation.

This work differs from the existing neuroanatomy primers. Our overall objective is to make the presentation and understanding of human brain anatomy quick and easy. In order to achieve this objective:

W. L. Nowinski (✉)
John Paul II Center for Virtual Anatomy and Surgical Simulation, University of Cardinal Stefan Wyszynski, Warsaw, Poland

Department of Radiology, University of Washington, Seattle, WA, USA
e-mail: w.nowinski@uksw.edu.pl

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- The presentation of neuroanatomy is in three dimensions (3D) with additional supportive planar images in the orthogonal (axial, coronal, and sagittal) planes.
- The brain is subdivided into structure, vasculature, and connections (white matter tracts); consequently, we consider structural, vascular, and connectional neuroanatomies.
- 3D cerebral models of structure, vasculature, and tracts are mutually consistent spatially, because they were derived from the same brain living specimen.
- 3D cerebral models and the planar images are fully parcellated; each parcellated object is uniquely colored.
- 3D cerebral models and the planar images are completely labelled (named); as a terminology we use the *Terminologia Anatomica* [75].
- 3D cerebral models are electronically dissectible into modules, groups, and individual components allowing the atlas user for a fast scene composing (structure assembly and/or disassembly).

In this work I use my digital brain atlases that have been developed for more than two decades [63–69] (see the recent editorial [117]). The 3D cerebral models have been created from multiple 3 and 7 Tesla magnetic resonance scans of my brain [69]. The development of the atlases is addressed in [78–82], tools for their creation in [77], techniques for modelling of cerebral structures in [76, 78, 92], and atlas-based applications in [79–91].

The recent (i.e. from the first edition of this book) developments in our brain atlasing are covered in [93–116], including the extension of the virtual brain to the head and neck. They also contain an overview of computational and mathematical methods for brain atlasing [115] and future directions [116].

2.2 Structural (Gross) Neuroanatomy

We present parcellation (subdivision) of the brain in 3D followed by sectional neuroanatomy. The stereotactic target structures and functional cortical areas also are outlined.

2.2.1 Brain Parcellation

The central nervous system consists of the *brain* and the *spinal cord*. The brain encases the fluid-filled *ventricular system* and is parcellated into three main components[1] (Fig. 2.1a):

[1] We follow here the brain parcellation as in, e.g. [16]. Some other sources (e.g. [18]) subdivide the brain into the cerebrum, diencephalon, cerebellum, and brainstem.

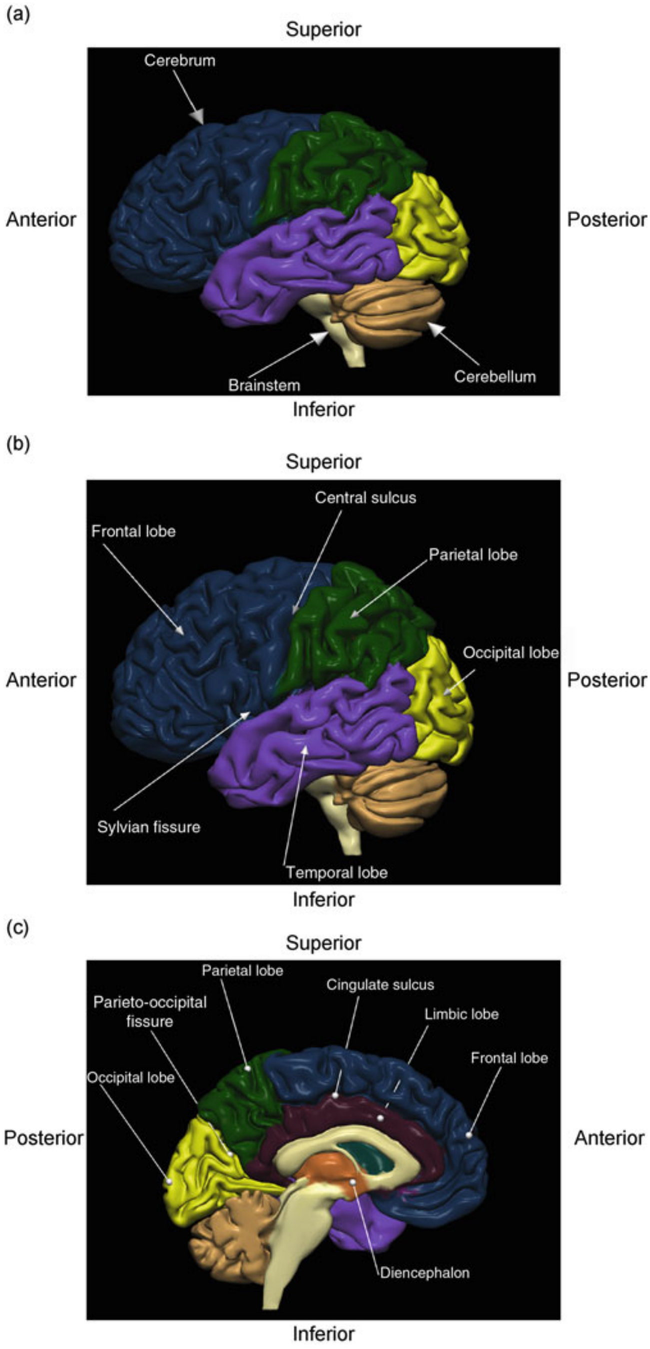


Fig. 2.1 Gross anatomy of the left cerebral hemisphere: (**a**) brain parcellation; (**b**) lobes, lateral view; (**c**) lobes, medial view

- *Cerebrum*
- *Cerebellum* (the little brain)
- *Brainstem*

The cerebrum comprises:

- Left and right *cerebral hemispheres*
- Interbrain between the cerebrum and the brainstem termed the *diencephalon*
- *Deep grey nuclei* (other than diencephalic)

The cerebral hemispheres are the largest compartment of the brain, and they are interconnected by white matter fibres (see Sect. 2.4.2). The hemispheres are composed of:

- Outer *grey matter* termed the *cerebral cortex*
- Inner *white matter* encompassing the diencephalon and deep grey nuclei

The grey matter contains mainly nerve cell bodies, while the white matter is made up predominantly of nerve fibres (axons). The cerebral cortex is highly convoluted. These folds form so-called *gyri* that are separated by grooves termed *sulci* or *fissures* (deep sulci). The cerebral hemispheres are parcellated into five *lobes* (Fig. 2.1b, c):

- *Frontal lobe*
- *Temporal lobe*
- *Parietal lobe*
- *Occipital lobe*
- *Limbic lobe*

The *insula* is sometimes classified as the (sixth) *central* or *insular lobe*. The lobes are partly demarcated by the sulci/fissures (Fig. 2.1). The *central sulcus* separates the frontal lobe anterior from the parietal lobe posterior (Fig. 2.1b). The *Sylvian* (*lateral*) *fissure* demarcates the temporal lobe below from the frontal and parietal lobes above (Fig. 2.1b). The *parieto-occipital fissure* separates the parietal lobe anterior from the occipital lobe posterior (Fig. 2.1c). The *cingulate sulcus* separates the frontal lobe above from the limbic lobe below (Fig. 2.1c).

The diencephalon contains numerous nuclei grouped into four parts (Fig. 2.1c):

- *Thalamus* (see also Fig. 2.6)
- *Subthalamus* including the *subthalamic nucleus* (see Sect. 2.2.6)
- *Hypothalamus* (see also Fig. 2.10a)
- *Epithalamus* (comprising the pineal gland)

The cerebellum is composed of (Fig. 2.2a):

- Left and right *cerebellar hemispheres*
- Midline *vermis* which unites them

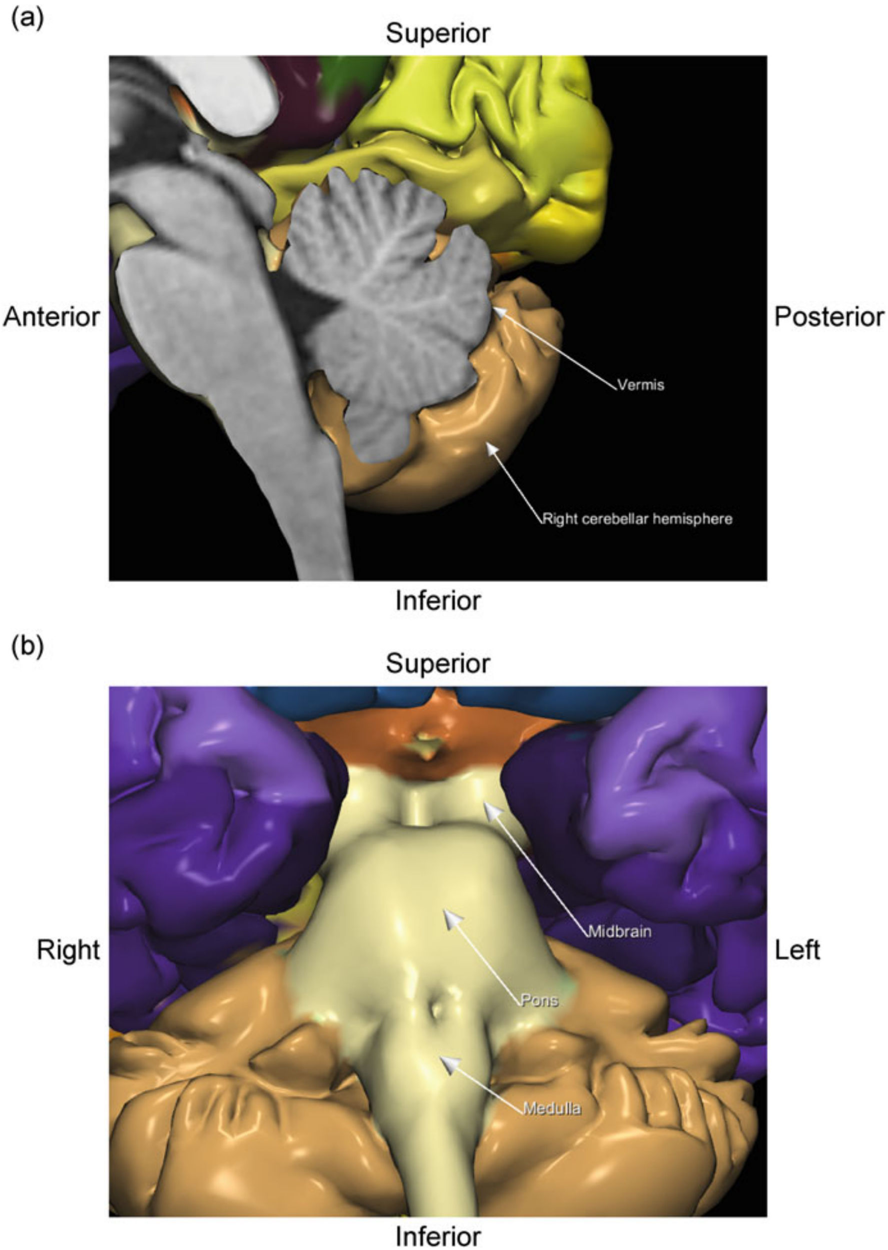


Fig. 2.2 Cerebellum and brainstem: (**a**) right cerebellum (medial view); (**b**) midbrain, pons, and medulla of the brainstem (infero-anterior view)

The brainstem is subdivided into (Fig. 2.2b):

- *Midbrain*
- *Pons*
- *Medulla (oblongata)*

2.2.2 Cortical Areas

The cortex has three surfaces: lateral, medial, and inferior (also called basal or ventral). Moreover, the transitional areas form the frontal, temporal, and occipital poles (see, e.g. Figs. 2.5 and 2.27).

2.2.2.1 Lateral Cortical Surface

Four lobes are present on the lateral cortical surface: frontal, temporal, parietal, and occipital (Fig. 2.1b). The lateral surface of the frontal lobe is subdivided by three sulci (the *superior frontal sulcus*, *inferior frontal sulcus*, and *precentral sulcus*) into four gyri (Fig. 2.3):

- *Superior frontal gyrus*
- *Middle frontal gyrus*
- *Inferior frontal gyrus*
- *Precentral gyrus*

The lateral surface of the temporal lobe is subdivided by two sulci (the *superior temporal sulcus* and *inferior temporal sulcus*) into three gyri (Fig. 2.3):

- *Superior temporal gyrus*
- *Middle temporal gyrus*
- *Inferior temporal gyrus*

The lateral surface of the parietal lobe is subdivided by two sulci (the *postcentral sulcus* and *intraparietal sulcus*) into three gyri (Fig. 2.3):

- *Postcentral gyrus*
- *Superior parietal gyrus* (*lobule*)
- *Inferior parietal gyrus* (*lobule*)
  - *Supramarginal gyrus*
  - *Angular gyrus*

The lateral surface of the occipital lobe is subdivided by two sulci (the *superior occipital sulcus* and *inferior occipital sulcus*) into three gyri (Fig. 2.3):

- *Superior occipital gyrus*
- *Middle occipital gyrus*
- *Inferior occipital gyrus*

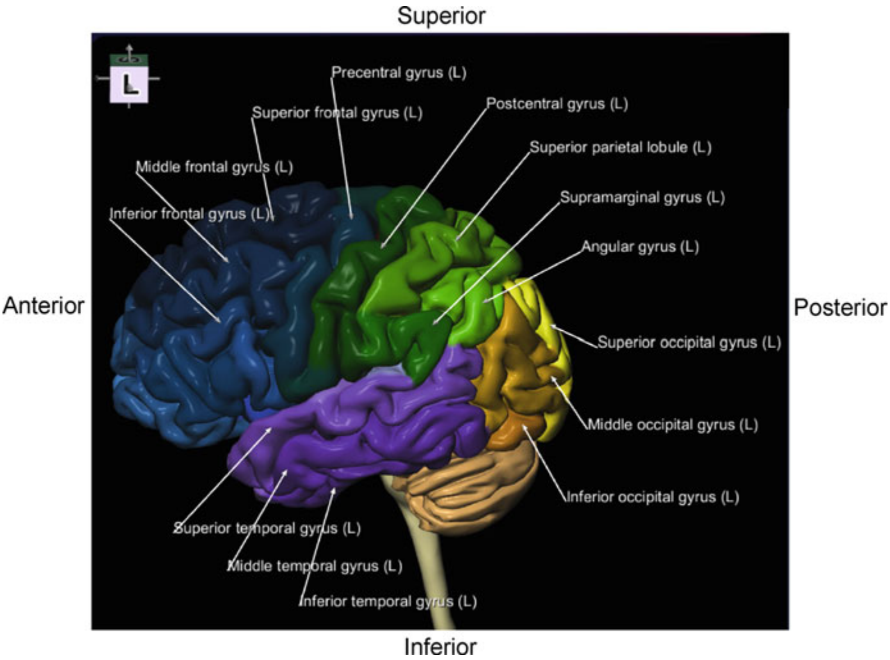


Fig. 2.3 Cortical areas of the left (L) hemisphere: lateral view. The orientation box located in the top-left corner indicates the viewing direction (L, left; R, right; S, superior (dorsal); I, inferior (ventral); A, anterior; and P, posterior). Each gyrus is assigned a unique color

2.2.2.2 Medial Cortical Surface

The frontal, parietal, occipital, and limbic lobes are present on the medial surface of the cortex (Fig. 2.1c). The limbic lobe contains the gyri located at the inner edge (or *limbus*) of the hemisphere including (Fig. 2.4):

- *Subcallosal gyrus* (*areas*)
- *Cingulate gyrus*
- *Isthmus* (*of cingulate gyrus*)
- *Parahippocampal gyrus*

The *medial frontal gyrus* and the *paracentral lobule* separated from the limbic lobe by the *cingulate sulcus* (Fig. 2.1c) occupy most of the medial surface of the frontal lobe (Fig. 2.4). The parietal lobe includes the *precuneus* (Fig. 2.4) separated from the occipital lobe by the *parieto-occipital fissure* (Fig. 2.1c). The occipital lobe comprises the *cuneus* and the *lingual gyrus* separated by the *calcarine sulcus* (*fissure*) (Fig. 2.4).

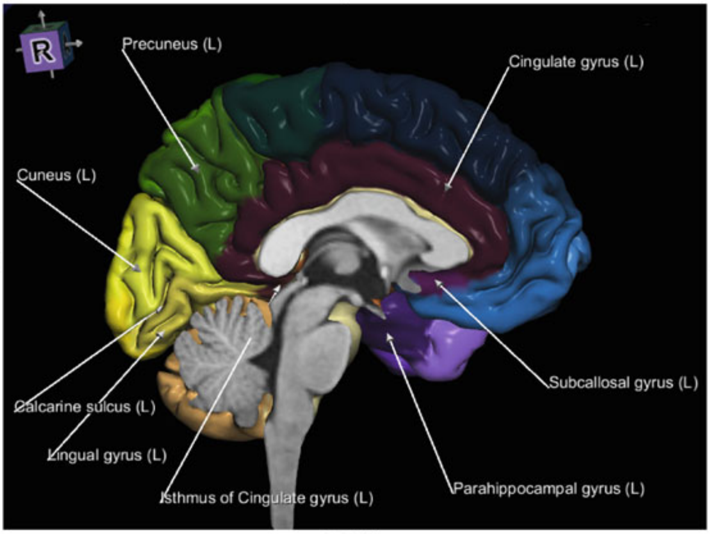


Fig. 2.4 Cortical areas of the left hemisphere: medial view

2.2.2.3 Inferior Cortical Surface

The inferior surface of the cortex includes the frontal, temporal, and occipital lobes. The frontal lobe comprises (Fig. 2.5):

- *Straight gyrus*
- *Orbital gyri* parcellated by the approximately *H-shaped sulcus* into the *anterior, medial, lateral, and posterior orbital gyri*

The temporal and occipital lobes are subdivided by two sulci (the *lateral occipitotemporal sulcus* and *medial occipitotemporal* (*collateral*) *sulcus*) into three gyri (Fig. 2.5):

- *Medial occipitotemporal gyrus* whose temporal part constitutes the *parahippocampal gyrus* and the occipital part the *lingual gyrus*
- *Lateral occipitotemporal gyrus* (called also the *fusiform gyrus*)
- *Inferior temporal gyrus*

2.2.3 Deep Grey Nuclei

The deep grey nuclei are paired grey matter structures. The main deep grey nuclei (other than the diencephalic nuclei discussed in Sect. 2.2.1) are (Fig. 2.6):

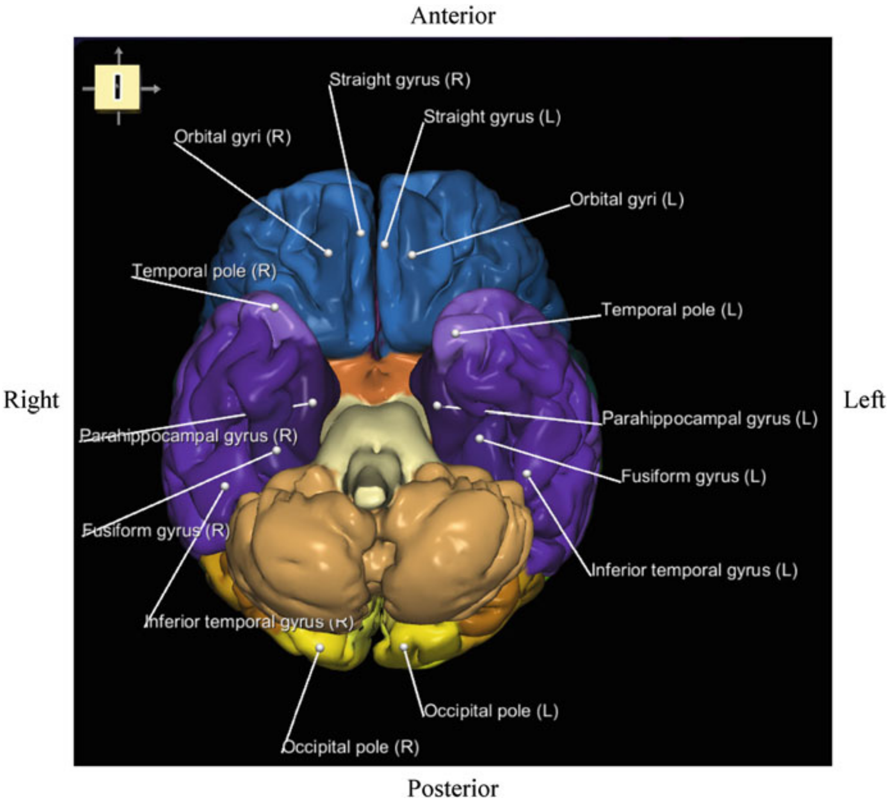


Fig. 2.5 Cortical areas: inferior view

- *Basal ganglia* (*nuclei*)
  - *Caudate nucleus*
  - *Lentiform nucleus*
    - *Putamen*
    - *Globus pallidus*
      - *Lateral* (*or outer*) *segment*
      - *Medial* (*or inner*) *segment* (see also Sect. 2.2.6)
- *Hippocampus*
- *Amygdala* (*amygdaloid body*)

The putamen and the caudate nucleus form the *striatum*.

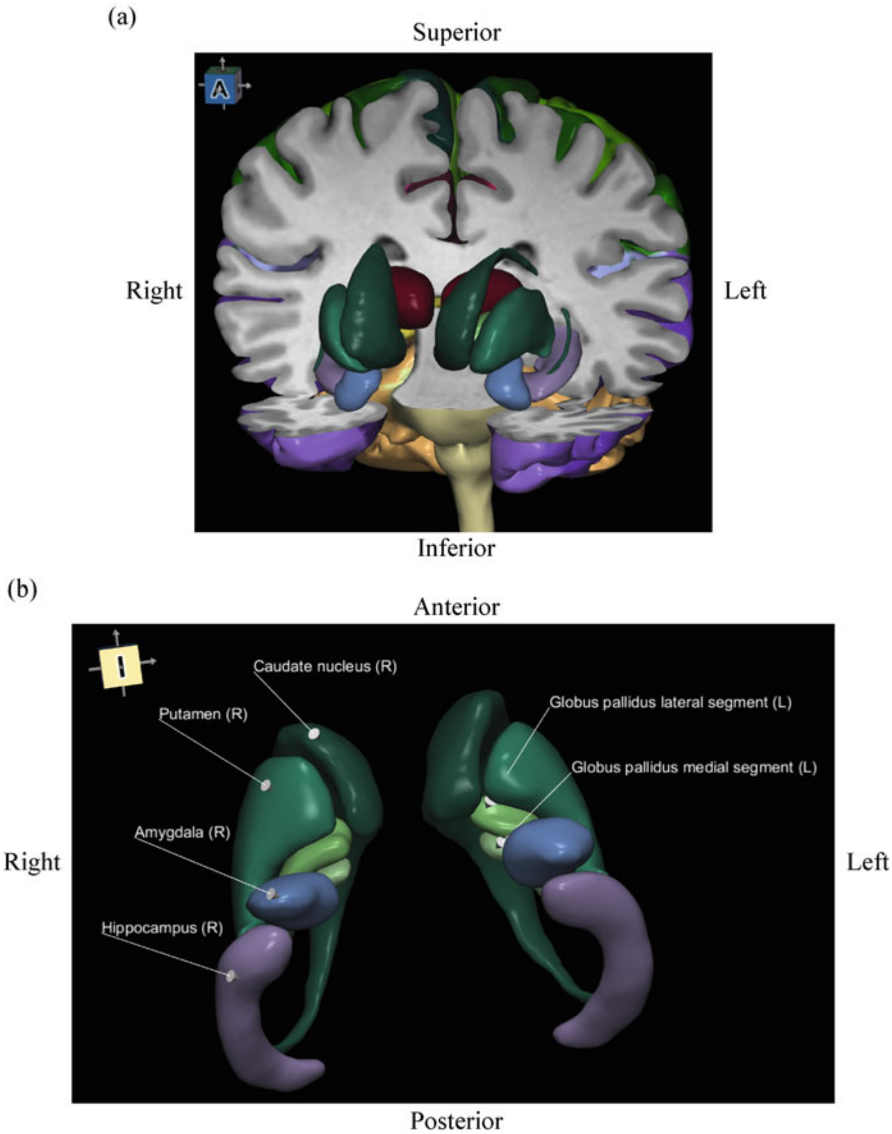


Fig. 2.6 Deep grey nuclei: (**a**) embedded into the brain (anterior view); (**b**) shown in isolation (inferior view); note: the arrowheads indicate the pointed structures

(a) (b)

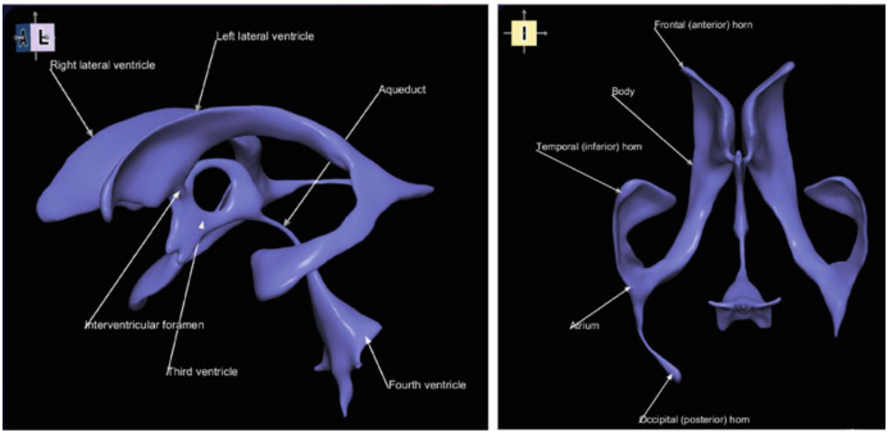


Fig. 2.7 Ventricular system: (**a**) interconnected ventricles; (**b**) components of the lateral ventricle (inferior view)

2.2.4 Ventricular System

The ventricular system contains four interconnected cerebral ventricles (cavities) filled with *cerebrospinal fluid* (CSF) (Fig. 2.7a):

- Left and right *lateral ventricles*
- *Third ventricle*
- *Fourth ventricle*

CSF is secreted mainly in the *choroid plexus* (a network of vessels) and circulates from the lateral ventricles through the paired *interventricular foramina* (of Monro) to the third ventricle and then via the *aqueduct* to the fourth ventricle (Fig. 2.7a). The lateral ventricles are the largest and each contains (Fig. 2.7b):

- *Body* (or *central portion*)
- *Atrium* (or *trigon*)
- *Horns*
  - *Frontal* (*anterior*)
  - *Occipital* (*posterior*)
  - *Temporal* (*inferior*)

2.2.5 Sectional Neuroanatomy

Sectional (planar) neuroanatomy is typically presented on orthogonal (axial, coronal, and sagittal) images. In order to spatially locate the orthogonal images, we place them in the Talairach coordinate system [48], which is a stereotactic reference system based on the anterior and posterior commissures (see also Fig. 2.28a) with the origin at the centre of the anterior commissure (see also Figs. 2.8, 2.9, and 2.10).

Four axial images located at −12 mm, +1 mm, +12 mm, and +24 mm (where '−' denotes the level below and '+' above the anterior commissure) with the cortical areas and deep grey nuclei segmented and labelled are shown in Fig. 2.8.

Two coronal images passing through the anterior and posterior commissures are presented in Fig. 2.9.

Two sagittal images located at 3 mm and 21 mm from the midline are shown in Fig. 2.10.

2.2.6 Main Stereotactic Target Structures

Several subcortical structures (and more recently also some cortical areas) are therapeutic stimulation targets in stereotactic and functional neurosurgery [83] to treat movement disorders (mainly Parkinson's disease), epilepsy, pain, and mental disorders (psychosurgery). The main stereotactic target structures are:

- *Subthalamic nucleus* (a part of the basal ganglia) (Fig. 2.11)
- *Ventrointermediate nucleus of the thalamus* (Fig. 2.12)
- *Globus pallidus interna* (medial segment) (Fig. 2.13)

The subthalamic nucleus presented on the triplanar (the axial, coronal, and sagittal planes) is shown in Fig. 2.11.

The ventrointermediate nucleus of the thalamus on the triplanar is presented in Fig. 2.12.

The globus pallidus interna on the triplanar is illustrated in Fig. 2.13.

All three target structures in 3D placed in the Talairach stereotactic coordinate system are shown in Fig. 2.14.

2.2.7 Functional Areas

Several parcellations are introduced to subdivide the cortical regions into functional areas [16]. Brodmann's parcellation that is based on histology (cytoarchitecture) is the most widely used, and it is illustrated in axial orientation in Fig. 2.15. *Brodmann's areas* are useful in neuroscience and functional studies because many

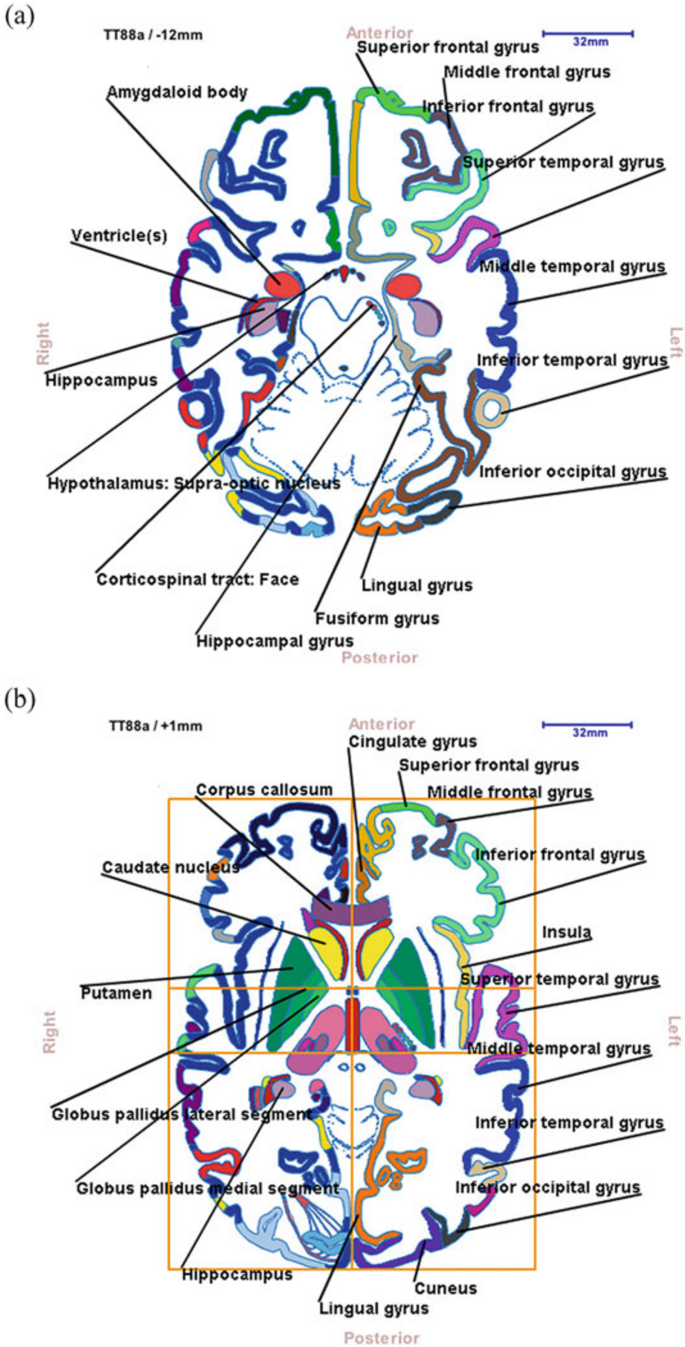
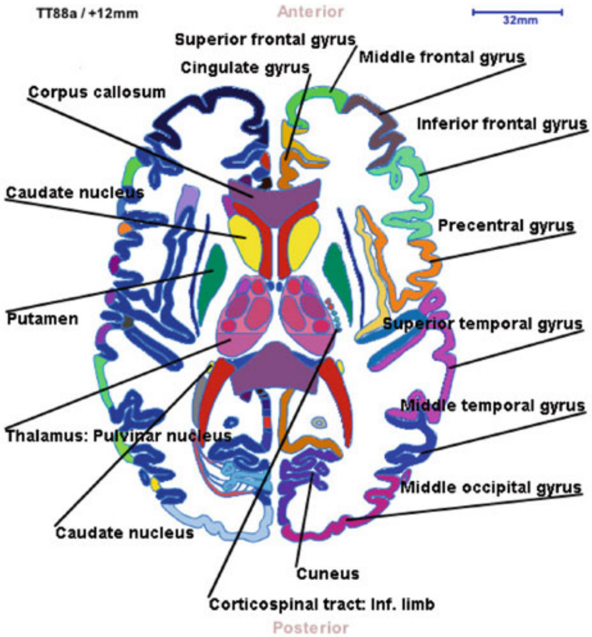


Fig. 2.8 Planar neuroanatomy in axial orientation at (**a**) −12 mm, (**b**) +1 mm (along with the Talairach grid), (**c**) +12 mm, and (**d**) +24 mm ('-' denotes the level below and '+' the level above the anterior commissure)

(c)



(d)

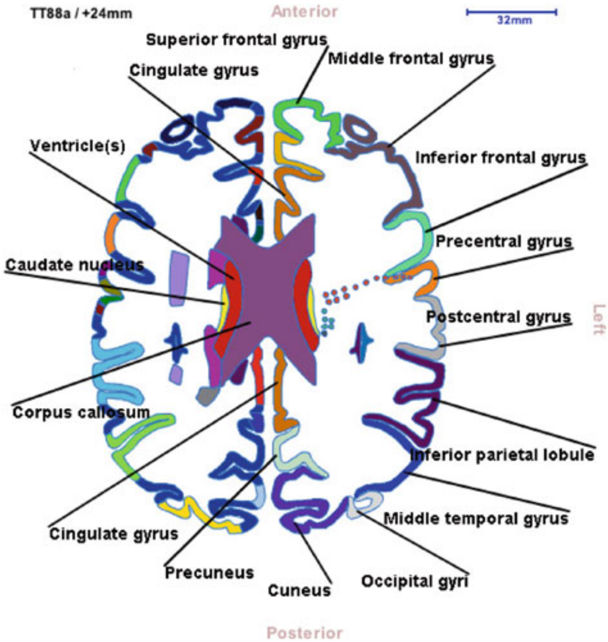


Fig. 2.8 (continued)

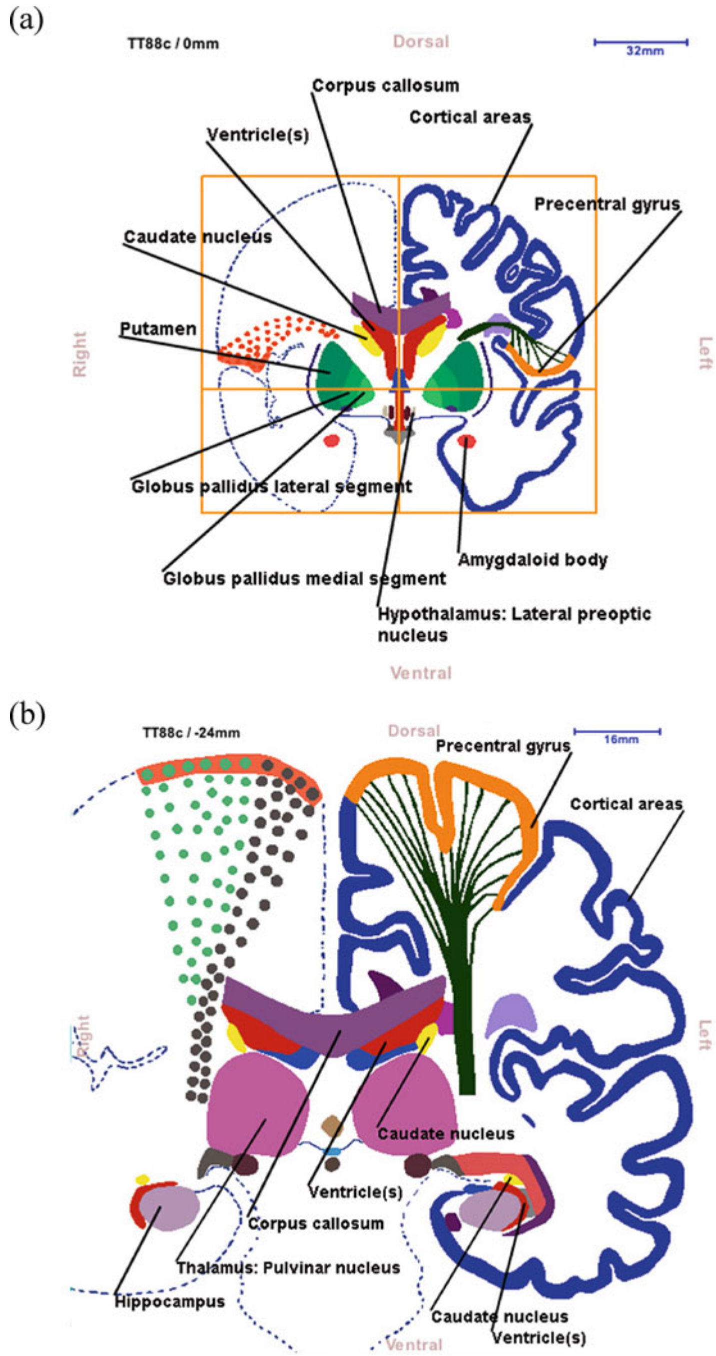


Fig. 2.9 Planar neuroanatomy in coronal orientation at (**a**) 0 mm passing through the anterior commissure (point), i.e. the location on the coronal plane where the horizontal and vertical planes of the Talairach coordinate system intersect, and (**b**) −24 mm passing through the posterior commissure (point)

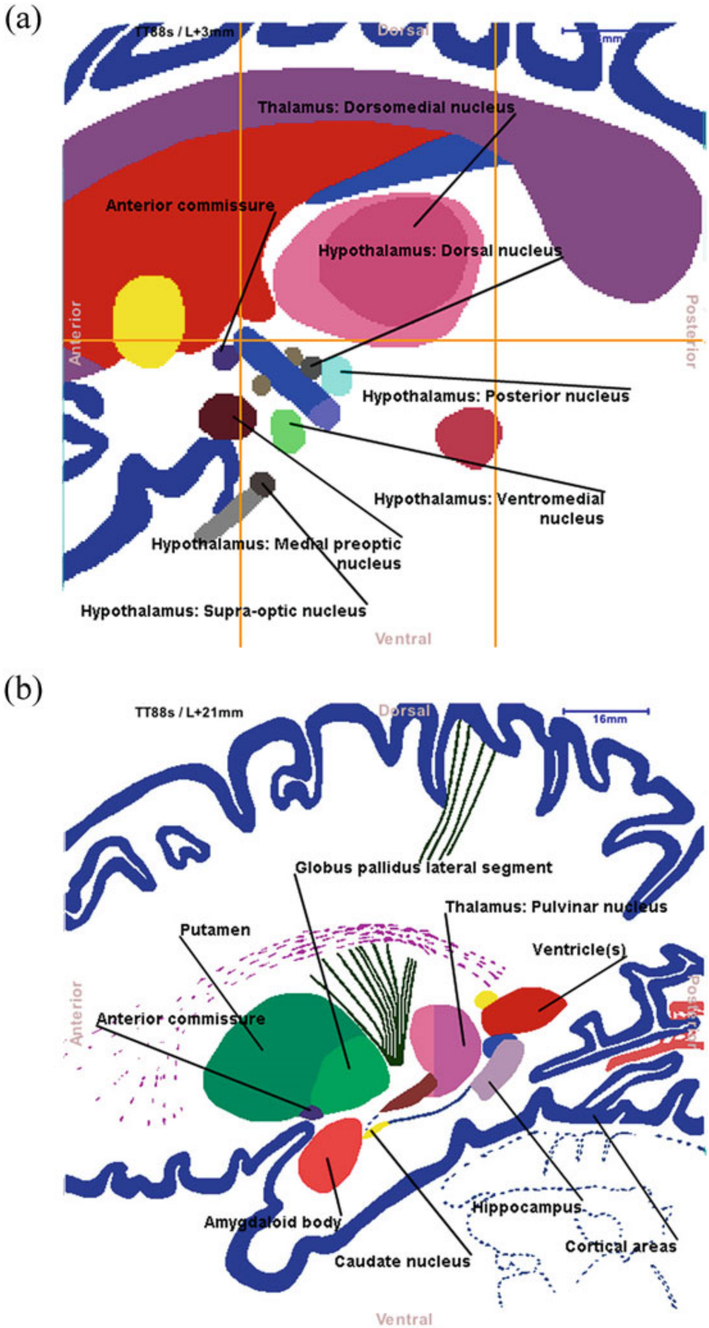


Fig. 2.10 Planar neuroanatomy in sagittal orientation at (**a**) 3 mm (along with the Talairach grid) and (**b**) 21 mm from the midline

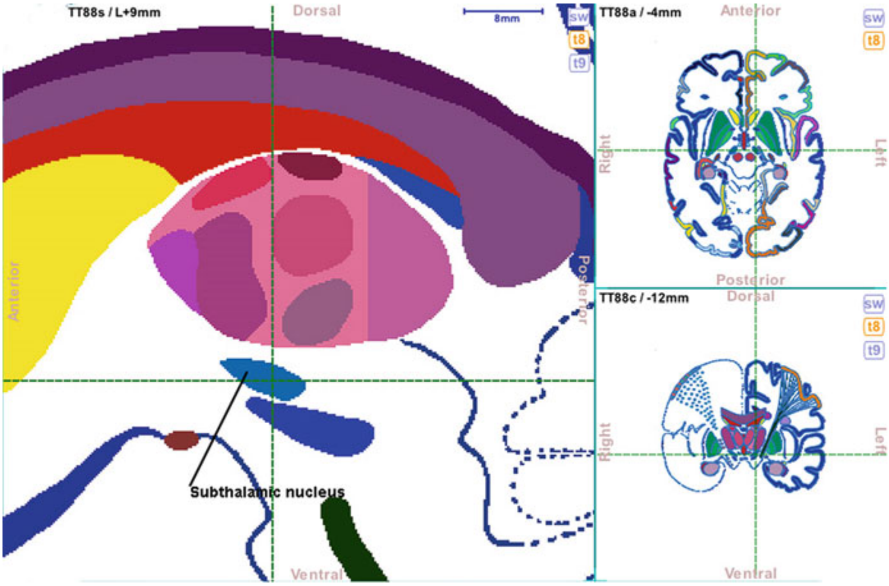


Fig. 2.11 Subthalamic nucleus on sagittal, axial, and coronal planes (the location of the triplanar is marked by the green dashed lines)

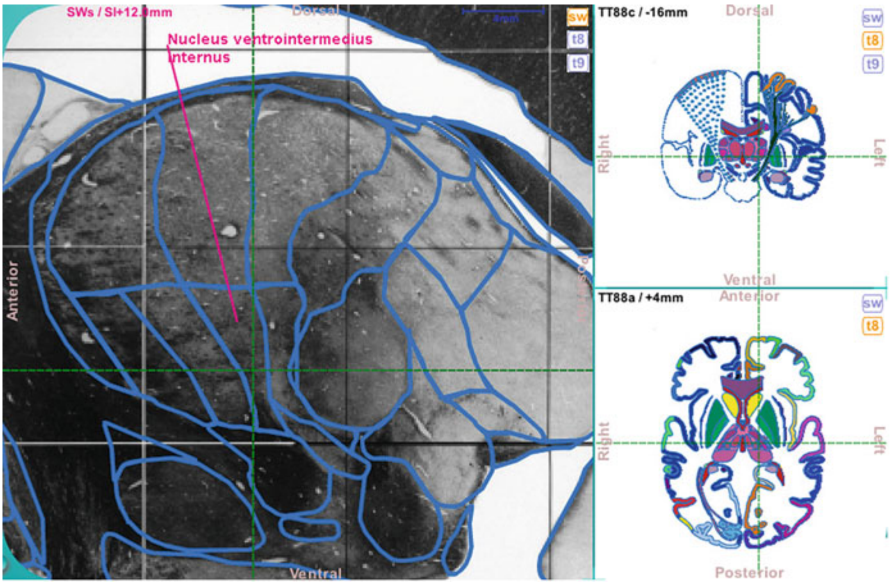


Fig. 2.12 Ventrointermediate nucleus of the thalamus on sagittal, coronal, and axial planes

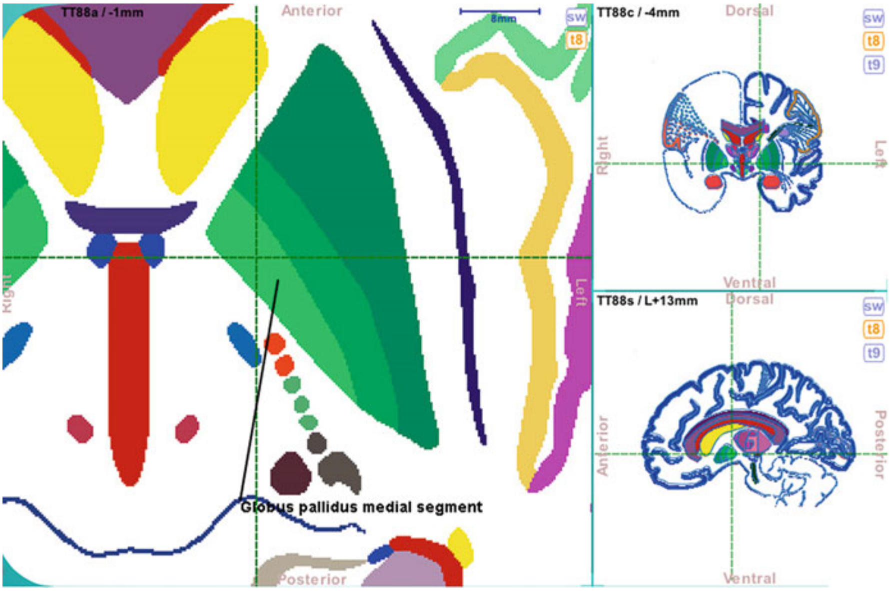


Fig. 2.13 Globus pallidus interna (medial segment) on axial, coronal, and sagittal planes

of Brodmann's areas, defined based on their neuronal organisation, have since been correlated closely to diverse cortical functions.

2.3 Vascular Neuroanatomy

The knowledge of cerebrovasculature is crucial in stroke, vascular, and tumour surgery as well as interventional neuroradiology. The complete cerebrovasculature is highly complex and variable (Fig. 2.16). It is subdivided into:

- *Arterial system*
- *Venous system* with the *cerebral veins* and *dural sinuses*

2.3.1 Arterial System

2.3.1.1 Parcellation of Arterial System

The brain is supplied by two pairs of arteries, left and right *internal carotid arteries* anteriorly and left and right *vertebral arteries* posteriorly forming the *basilar artery* (Fig. 2.17a), that are interconnected by the *circle of Willis* (Fig. 2.21).

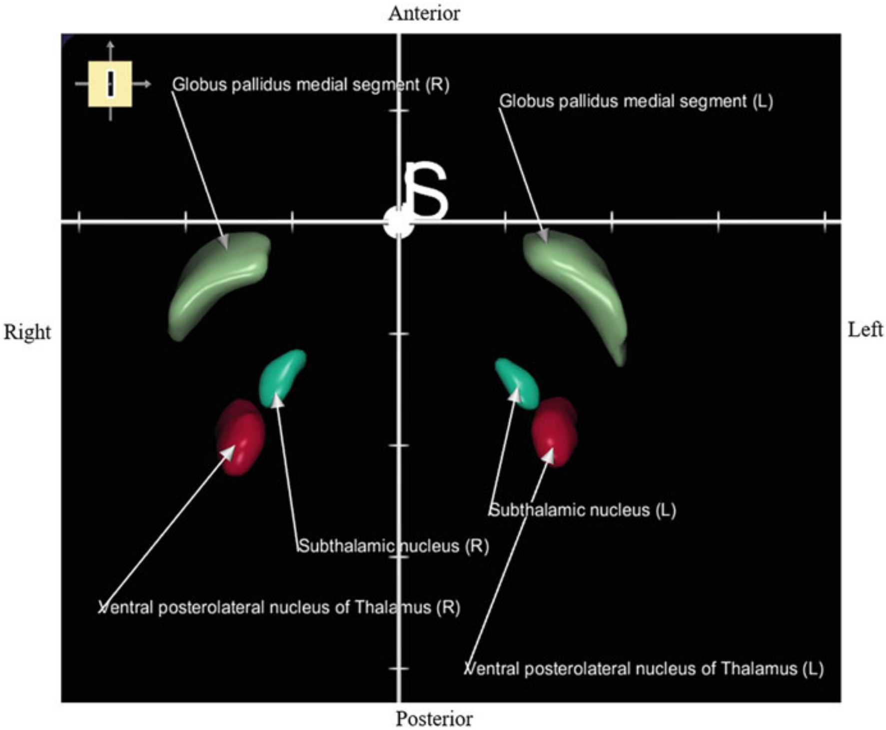


Fig. 2.14 Stereotactic target structures in 3D. The marks on the axes are placed at 10 mm intervals

The internal carotid artery branches into the *anterior cerebral artery* (Fig. 2.17c) and the *middle cerebral artery* (Fig. 2.17d). The left and right *posterior cerebral arteries* originate from the basilar artery (Fig. 2.17e).

2.3.1.2 Anterior Cerebral Artery

The anterior cerebral artery (ACA) has the following main branches (Fig. 2.18):

- *A1 segment* (*precommunicating part*)
- *A2 segment* (*postcommunicating part*)
  - *Pericallosal artery*
  - *Callosomarginal artery*

2.3.1.3 Middle Cerebral Artery

The middle cerebral artery (MCA) is subdivided into four segments (Fig. 2.19a):

- *M1 segment* (*sphenoid part*)
- *M2 segment* (*insular part*)
- *M3 segment* (*opercular part*)
- *M4 segment* (*terminal part*)

The main MCA branches of the left hemisphere are shown in Fig. 2.19b.

2.3.1.4 Posterior Cerebral Artery

The posterior cerebral artery is parcellated into four segments (Fig. 2.20):

- *P1 segment* (*precommunicating part*)
- *P2 segment* (*postcommunicating part*)
- *P3 segment* (*lateral occipital artery*)
- *P4 segment* (*medial occipital artery*)

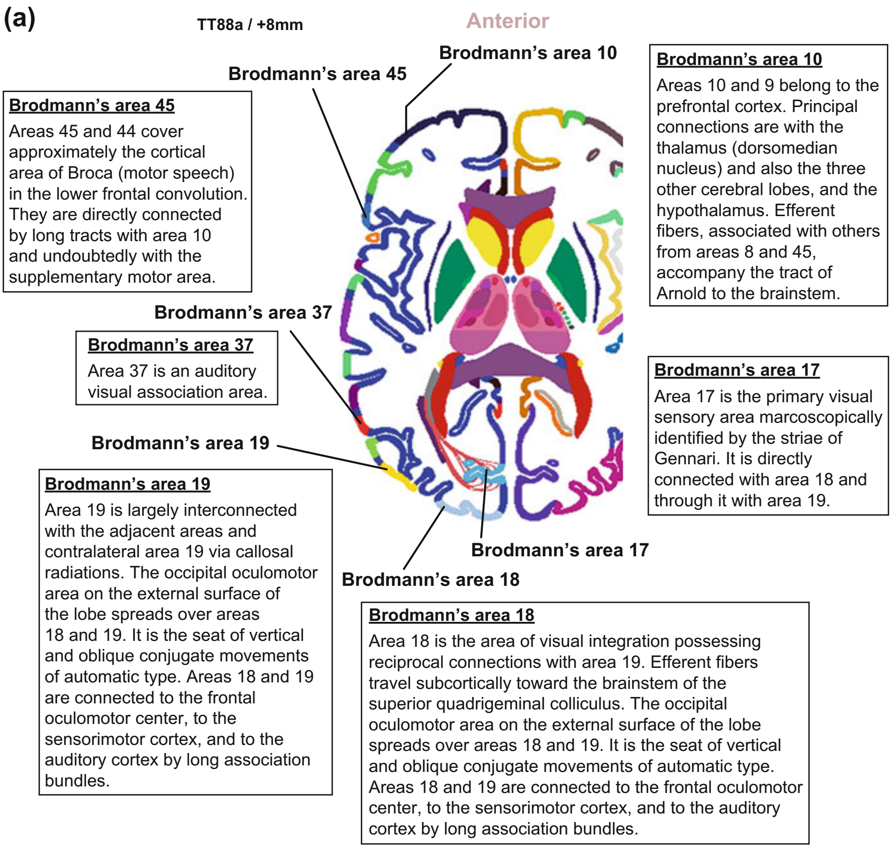


Fig. 2.15 Brodmann's areas in axial orientation: (**a**) vision and speech areas (+8 mm); (**b**) motor and sensory areas (+40 mm). The areas are uniquely color-coded

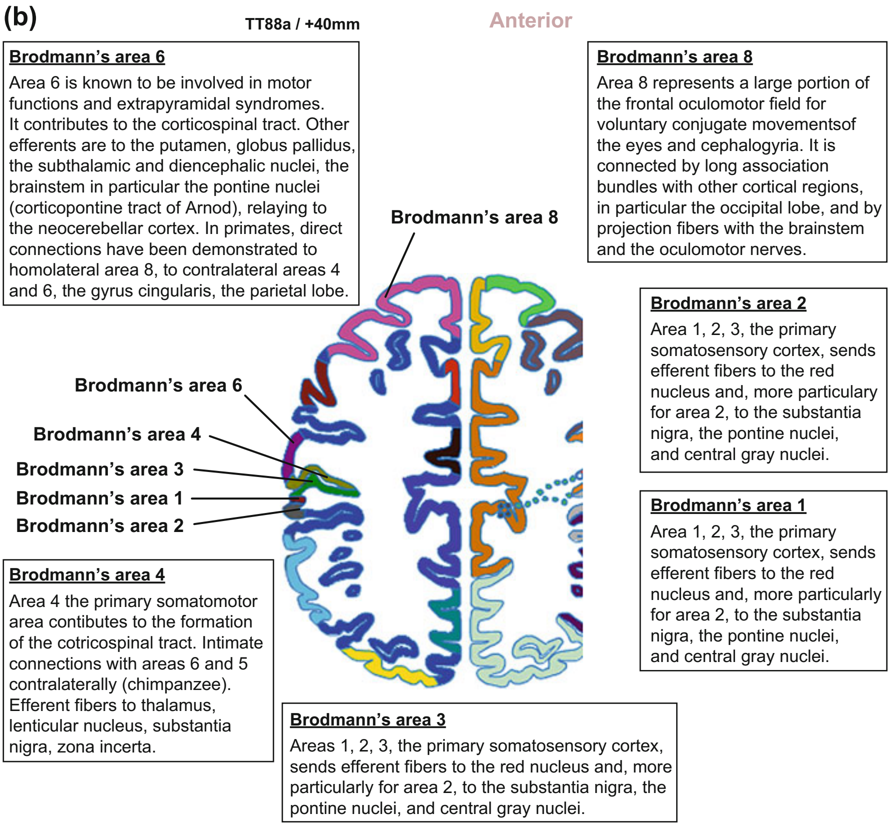


Fig. 2.15 (continued)

2.3.1.5 Circle of Willis

The circle of Willis connects the anterior and posterior circulations. It includes the following vessels (Fig. 2.21):

- *Anterior communicating artery*
- Left and right *posterior communicating arteries*
- Part of the left and right *internal carotid arteries*
- Left and right *A1 segments* of the anterior cerebral arteries
- Left and right *P1 segments* of the posterior cerebral arteries

2.3.2 Venous System

2.3.2.1 Parcellation of Venous System

The main components of the venous system are (Fig. 2.22):

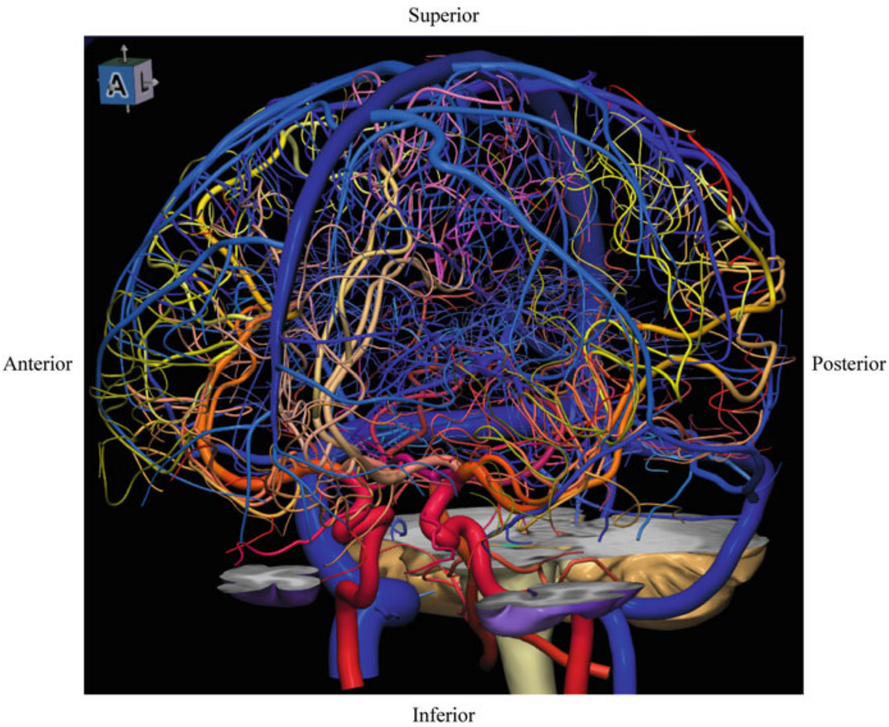


Fig. 2.16 The cerebral vasculature with arteries, veins, and dural sinuses. The vessels are uniquely color-coded such that all the vessels with the same name have the same color

- *Dural sinuses*
- *Cerebral veins*
  - *Superficial veins*
  - *Deep veins*

  The cerebral veins empty into the dural sinuses.

2.3.2.2 Dural Sinuses

The main dural sinuses are (Fig. 2.23):

- *Superior sagittal sinus*
- *Inferior sagittal sinus*
- *Straight sinus*
- Left and right *transverse sinuses*
- Left and right *sigmoid sinuses*

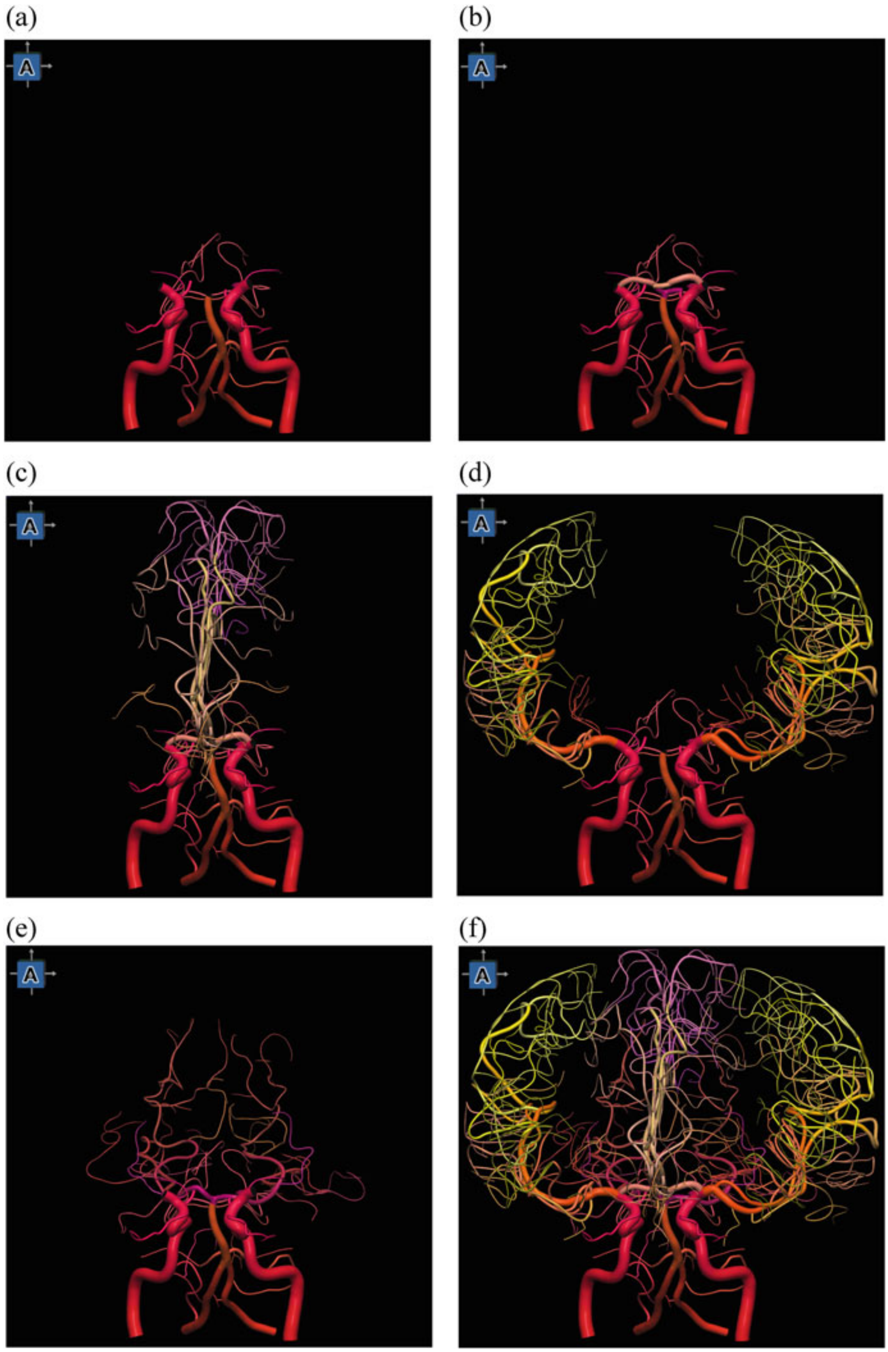


Fig. 2.17 The cerebral arteries: (**a**) blood supply to the brain by the internal carotid artery (ICA) anteriorly and the vertebral artery (VA) and the basilar artery (BA) posteriorly; (b) ICA and VA connected by the circle of Willis; (**c**) anterior cerebral artery along with the ICA, VA, and BA; (**d**) middle cerebral artery along with the ICA, VA, and BA; (**e**) posterior cerebral artery along with the ICA, VA, and BA; (**f**) complete arterial system

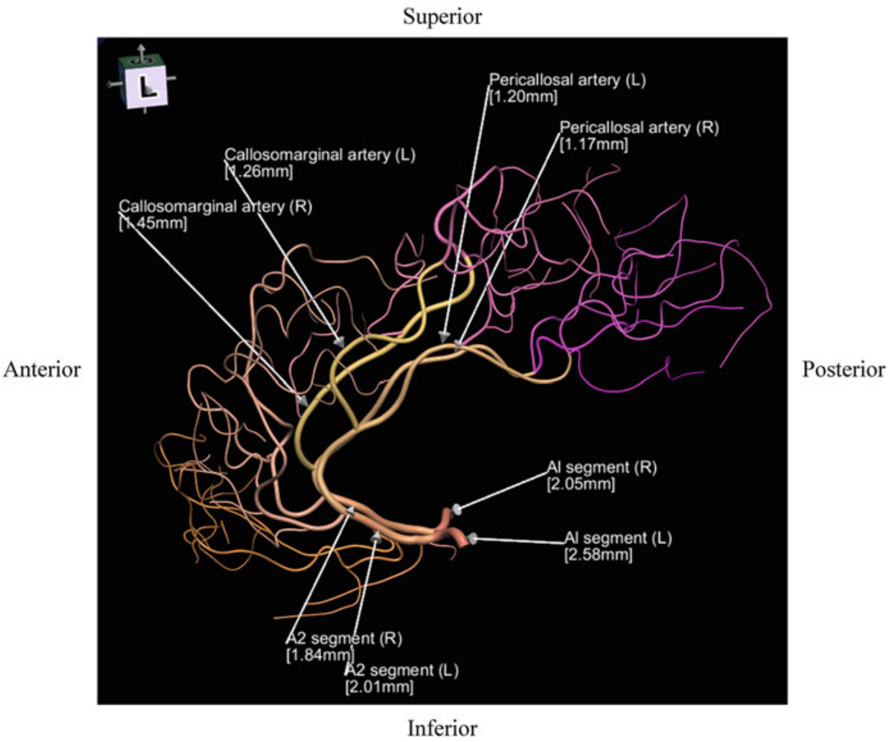


Fig. 2.18 Anterior cerebral artery. The vessel diameter at the arrowhead is given in the brackets

2.3.2.3 Cerebral Veins

The main superficial cerebral veins are (Fig. 2.24):

- *Frontopolar veins*
- *Prefrontal veins*
- *Frontal veins*
- *Parietal veins*
- *Occipital veins*

Other important superficial veins include the *superior* and *inferior anastomotic veins* and the *superficial middle cerebral vein*.

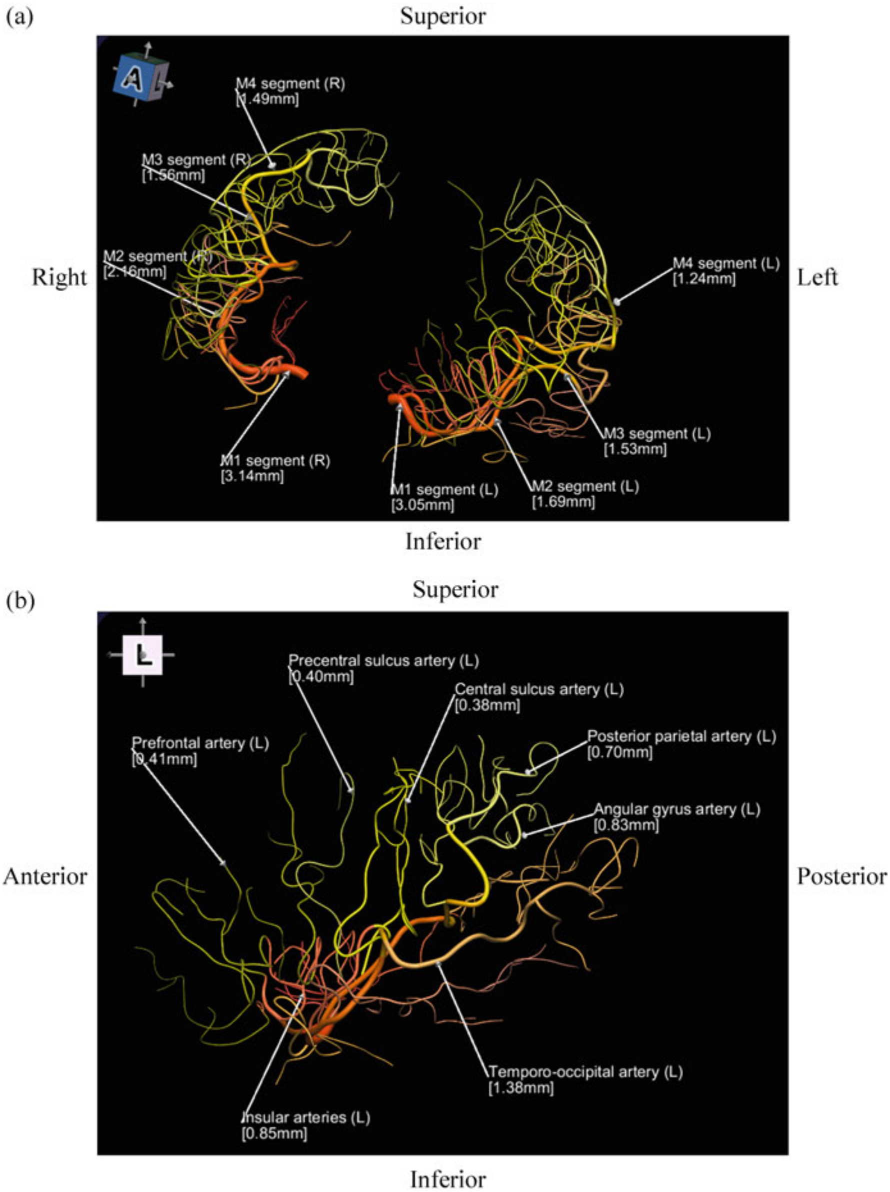


Fig. 2.19 Middle cerebral artery: (**a**) M1, M2, M3, and M4 segments; (**b**) main branches of the left hemisphere

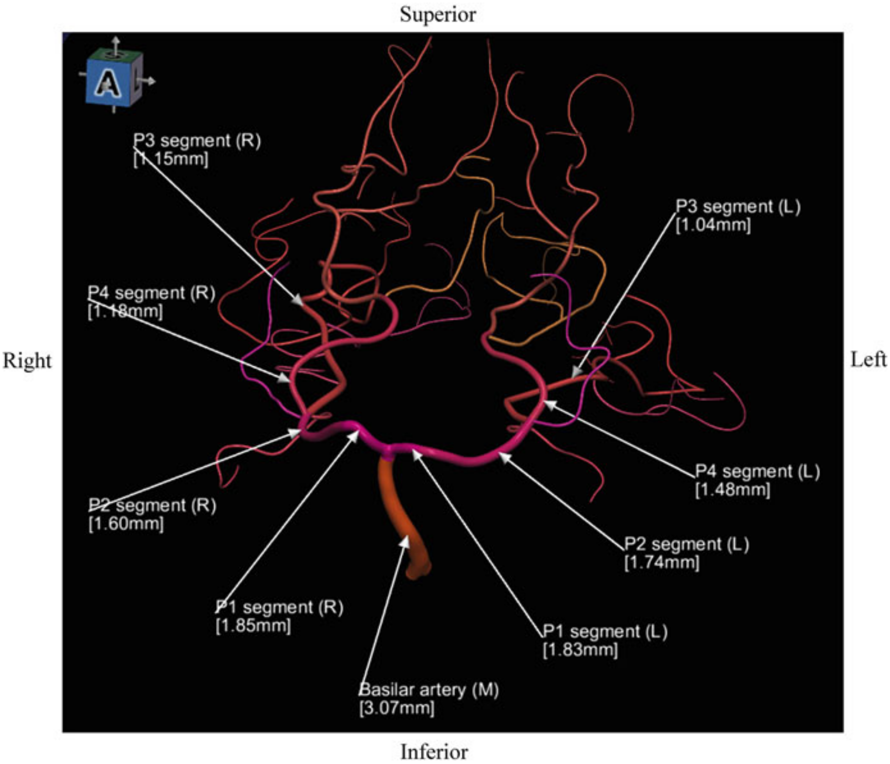


Fig. 2.20 Posterior cerebral artery

The main deep cerebral veins are (Fig. 2.25):

- *Great vein* (of Galen)
- Left and right *basal vein* (of Rosenthal)
- Left and right *internal cerebral veins*

2.3.3 Vascular Variants

The human cerebrovasculature is highly variable and vascular variants have been extensively studied (see, e.g. [6, 10, 13, 22]). Variations exist in terms of origin, location, shape, size, course, branching patterns, as well as surrounding vessels and structures. The knowledge of cerebrovascular variants is central in diagnosis, treatment, and medical education.

Some main variants of the circle of Willis synthesised in 3D are shown in Fig. 2.26 (more 3D vascular variants are presented in [70]).

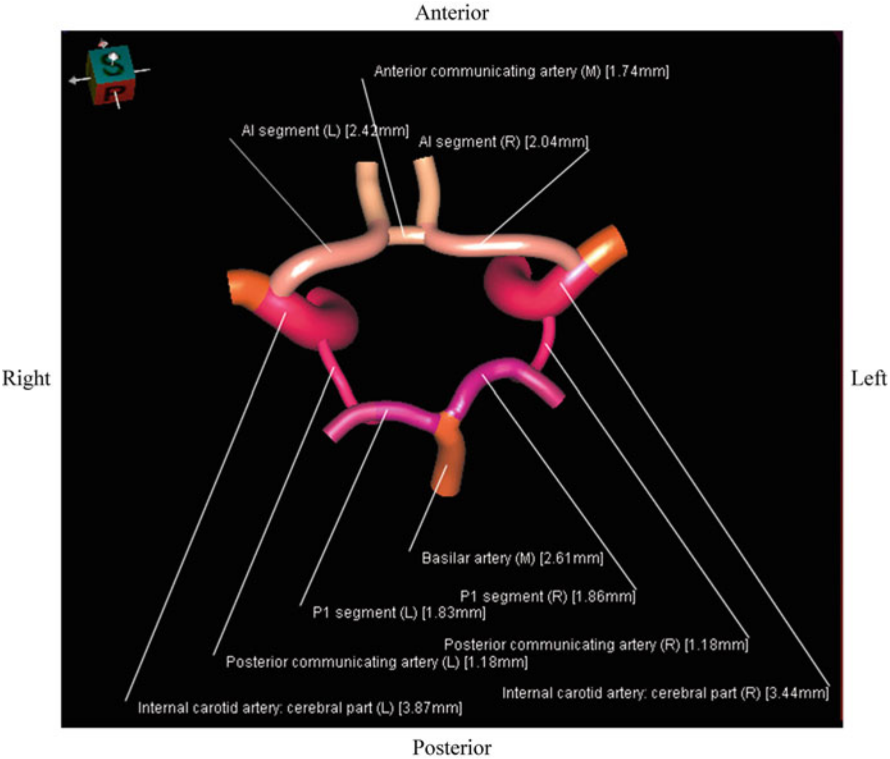


Fig. 2.21 The circle of Willis

2.4 Connectional Neuroanatomy

Three types of white matter connections (or tracts, fibres, bundles, fibre pathways, fascicles) are distinguished in the cerebral hemispheres (Fig. 2.27):

- *Commissural tracts*
- *Association tracts*
- *Projection tracts*

In addition, three cerebellar paired peduncles, *superior peduncle, middle peduncle*, and *inferior peduncle*, connect the cerebellum to the brainstem: midbrain, pons, and medulla, respectively.

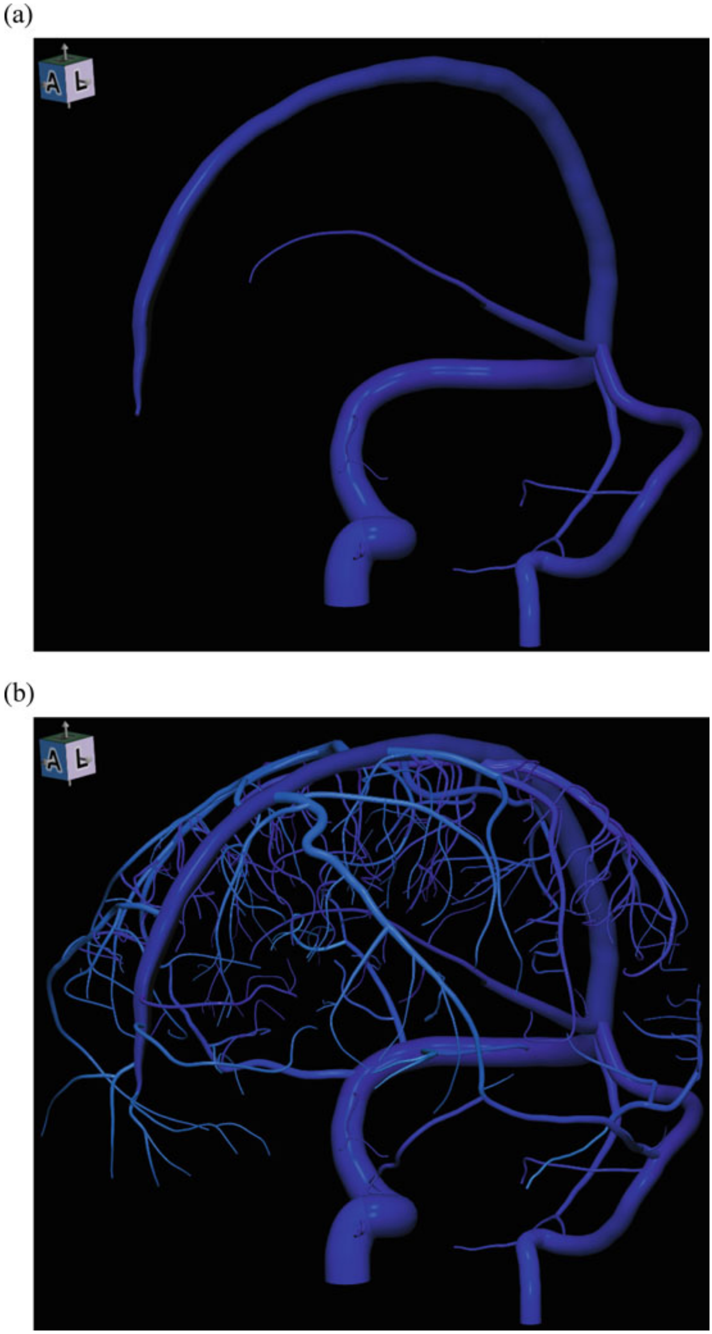
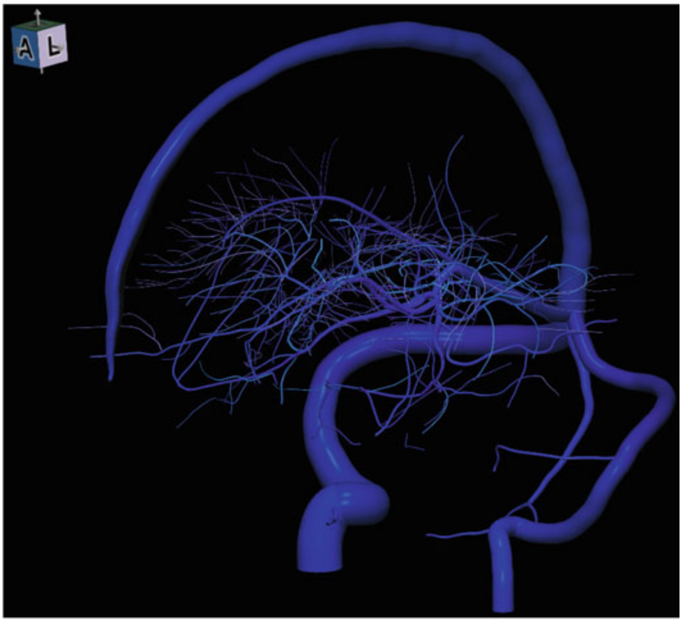


Fig. 2.22 Parcellation of the venous system: (**a**) dural sinuses (DS); (**b**) superficial veins with the DS; (**c**) deep veins with the DS; (**d**) complete venous system

(c)



(d)

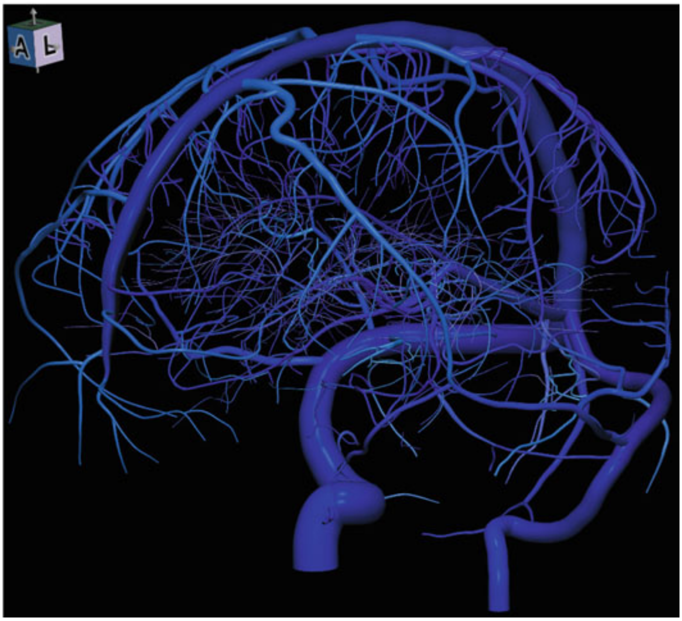
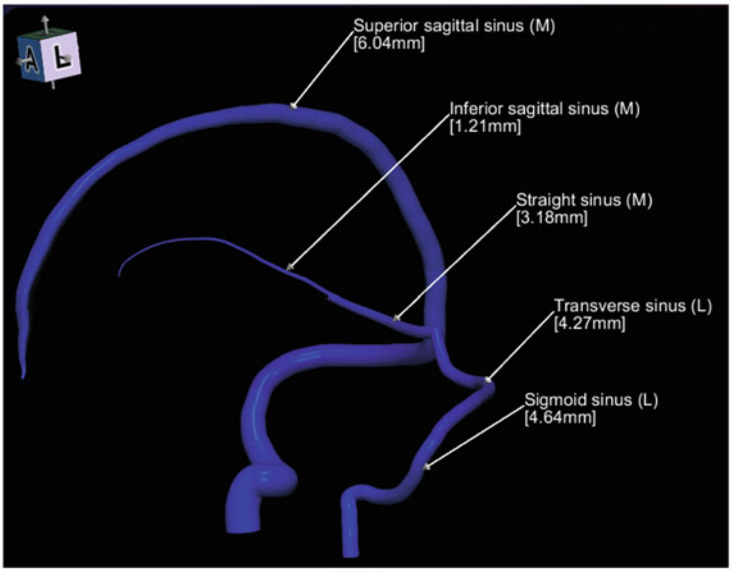


Fig. 2.22 (continued)

Superior

Anterior



Posterior

Inferior

Fig. 2.23 Dural sinuses (the midline and left hemisphere sinuses are labelled)

2.4.1 Commissural Tracts

The commissural tracts interconnect both hemispheres across the median plane. The main commissural tracts are (Fig. 2.28):

- *Corpus callosum*
- *Anterior commissure*
- *Posterior commissure*

The corpus callosum (the great commissure) is the largest commissure. Its three main parts: *genu* (knee), *body*, and *splenium*, connect the frontal lobes, wide areas of hemispheres, and the occipital lobes, respectively.

The anterior commissure connects the temporal lobes, while the posterior commissure links the midbrain, thalamus, and hypothalamus on both sides.

2.4.2 Association Tracts

The association tracts interconnect different cortical regions of the same cerebral hemisphere. There are two types of the association tracts:

- *Short arcuate* fibres that connect adjacent gyri (so-called U fibres)
- *Long arcuate* fibres interconnecting widely separated gyri

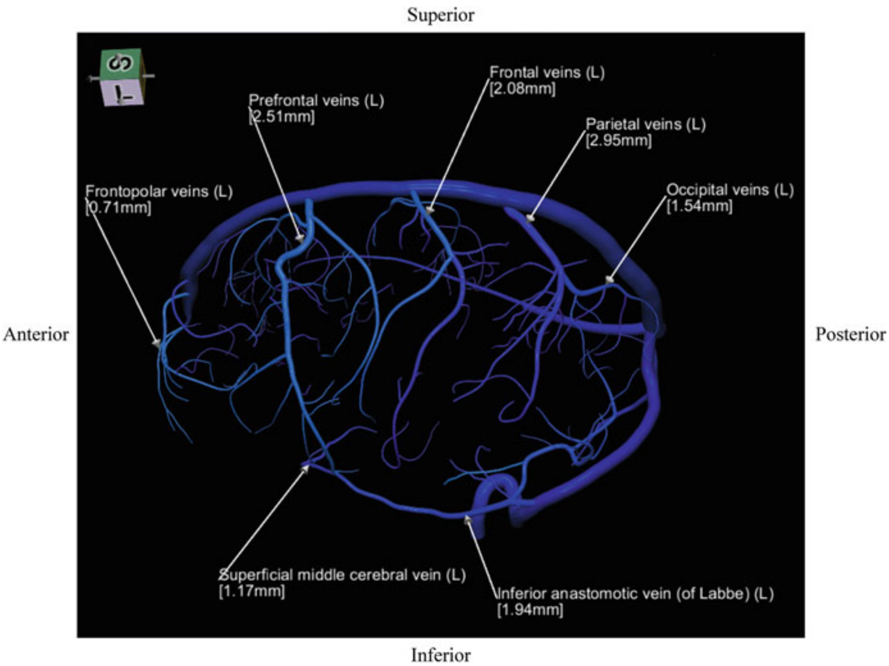


Fig. 2.24 Superficial cerebral veins of the left hemisphere

The main association tracts are (Fig. 2.29):

- *Superior longitudinal fasciculus*
- *Middle longitudinal fasciculus*
- *Inferior longitudinal fasciculus*
- *Superior occipito-frontal fasciculus*
- *Inferior occipito-frontal fasciculus*
- *Cingulum*
- *Uncinate fasciculus*

The superior longitudinal fasciculus connects the frontal lobe with the temporal, parietal, and occipital lobes. The inferior longitudinal fasciculus links the temporal lobe with the occipital lobe. The cingulum deep to the cingulated gyrus interconnects parts of the temporal, parietal, and occipital lobes. The uncinate fasciculus connects the frontal lobe (the orbital gyri and motor speech area) with the temporal lobe.

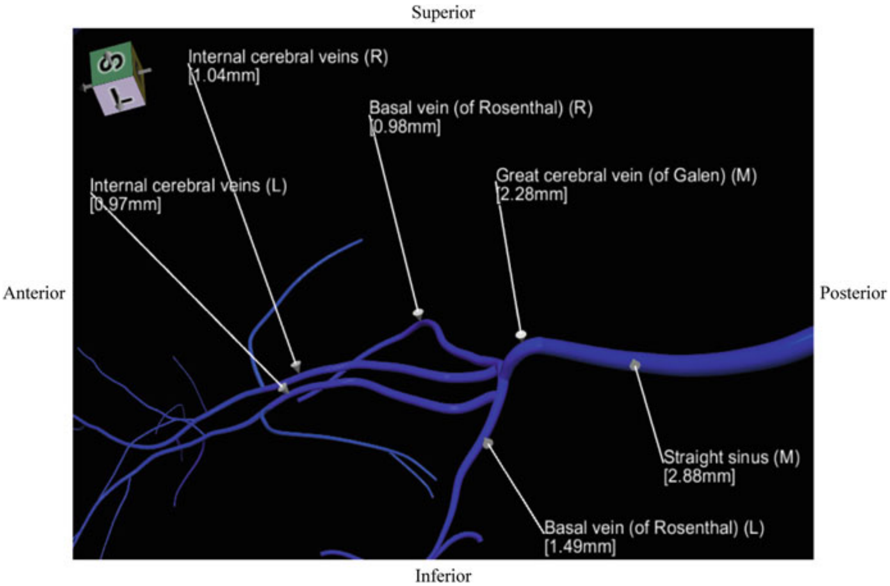


Fig. 2.25 Deep cerebral veins

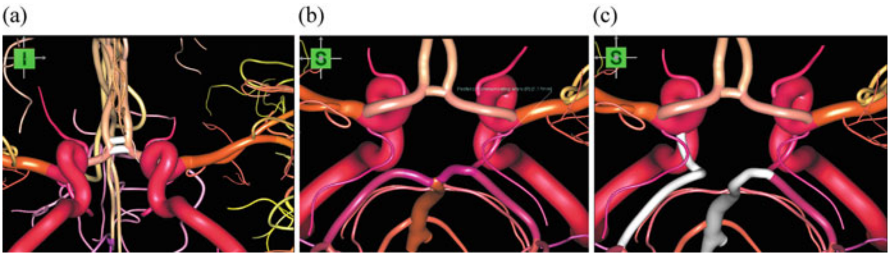


Fig. 2.26 Vascular variants of the circle of Willis: (**a**) double anterior communicating artery; (**b**) absent left posterior communicating artery; (**c**) absent left P1 segment (the variants are in white)

2.4.3 *Projection Tracts*

The projection tracts connect the cortex with the subcortical structures in the diencephalon, brainstem, and spinal cord. The main projection tracts are (Fig. 2.30):

- *Corticospinal* (*pyramidal*) *tract*
- *Corticothalamic tract* including the *anterior*, *posterior* (*optic*), and *superior thalamic radiations*
- *Corticobulbar tract* (connecting to the brainstem)
- *Corticopontine tract* (projecting to the pons)
- *Auditory radiations*

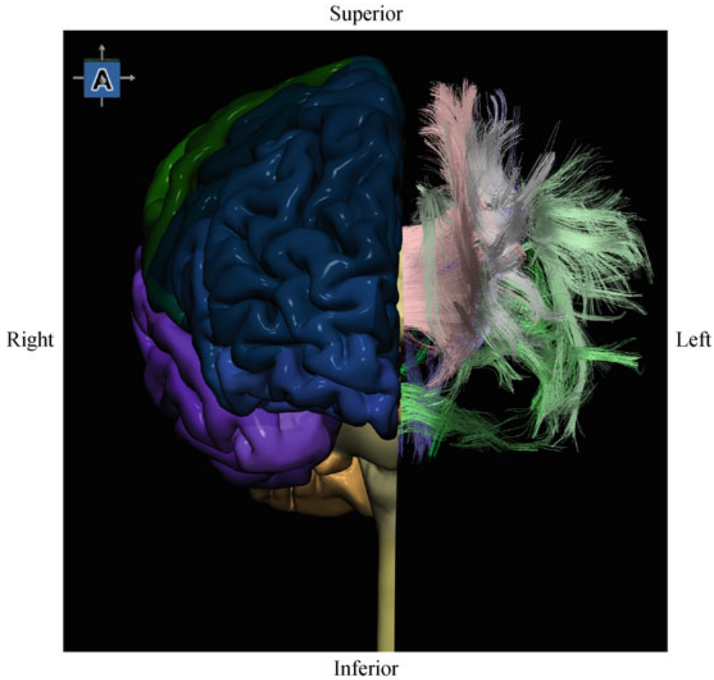


Fig. 2.27 White matter tracts of the left cerebral hemisphere; for comparison, the right hemisphere is shown. The tracts have been mapped by means of diffusion tensor imaging

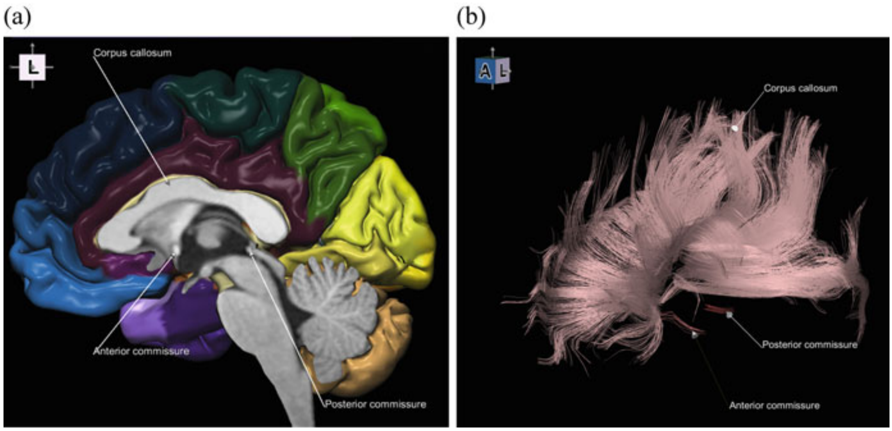


Fig. 2.28 Commissural tracts with the corpus callosum, anterior commissure, and posterior commissure: (**a**) on the midsagittal plane; (**b**) in 3D

The projection fibres located between the striatum and thalamus form the *internal capsule* consisting of the *anterior limb* (containing the corticothalamic tract), *genu*

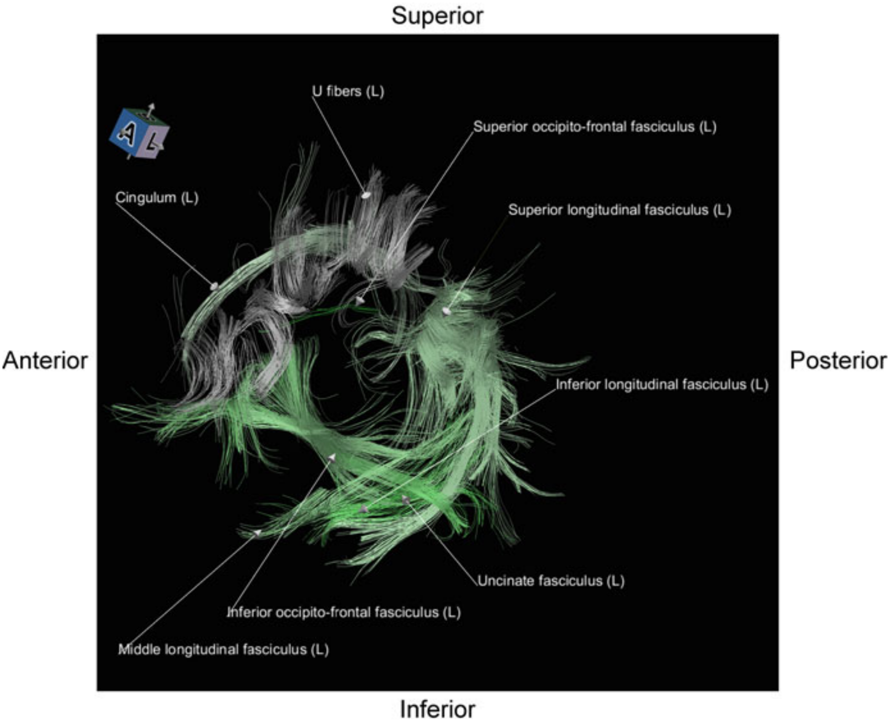


Fig. 2.29 Association tracts of the left cerebral hemisphere

(comprising the corticobulbar tract), and *posterior limb* (containing the corticospinal tract). The fibres radiating from the internal capsule to various parts of the cerebral cortex form the *corona radiata*.

2.5 Recent Extensions and Future Brain Atlas Developments

From the first edition of this book, our brain atlas work has substantially been advanced in terms of atlas creation and development of atlas-based applications. The taxonomy of our brain atlases, grouped into three families, has been presented in [109]. New atlas-based solutions have been proposed for stroke (the probabilistic stroke atlas for outcome prediction [110]), neuroradiology (an atlas assistance in image interpretation in multiple situations and in communication [108]), and neurology (the 3D atlas of neurologic disorders discussed below) [113].

We have created several new editions of the 3D anatomic and reference brain atlas and extended the virtual brain to the head and neck [93–96]. The existing tissue modules (such as the cortex [101] and white matter tracts [102]) have been

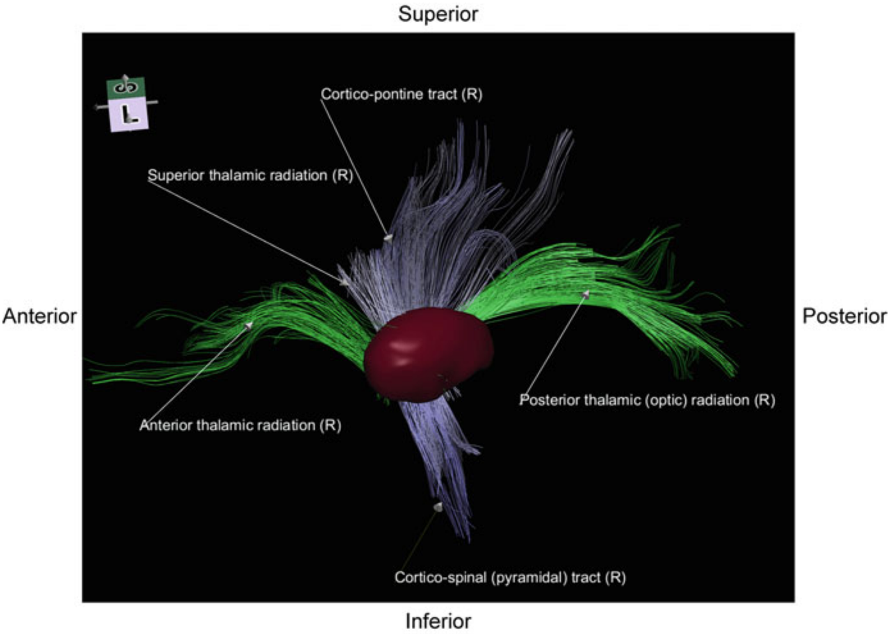


Fig. 2.30 Projection tracts of the right cerebral hemisphere along with the thalamus

further validated and new tissue modules created, including the cranial nerves with brainstem nuclei [103], extracranial arteries and veins [104], head muscles and glands [105], and skull [106]. The latest, most advanced neuroanatomic atlas is entitled *The Human Brain, Head and Neck in 2953 Pieces* [96]. A description of its content, functionality, and usefulness is addressed in [107]. Moreover, the publisher made this atlas publically available from www.thieme.com/nowinski (and also at http://www.wieslawnowinski.com/FreeBrainAtlas). The atlas is an ideal tool to study, explore, and teach brain anatomy extended to the head and neck. The virtual model is parcellated into about 3000 3D pieces. The atlas is interactive, 3D, fully parcellated, completely labelled, advanced, detailed, accurate, reference, realistic, of high resolution, spatially consistent, user-friendly, extendable (scalable), composable (enable to compose any scene), dissectible, explorable, stereotactic, and modular. It provides a user-friendly navigator enabling real-time structure and scan manipulation, 3D labelling of surface and sectional anatomy, structure assembling and disassembling, brain virtual dissection, interaction combined with animation, quantification (distances, vessel diameters, and stereotactic coordinates), and saving the composed and labelled scenes facilitating creation of teaching materials. The reader is encouraged to download this atlas and explore the beauty of virtual brain anatomy by him-/herself.

The neuroanatomic atlas has subsequently been extended towards neurology by creating a 3D interactive atlas of neurologic disorders providing a correspondence between a brain lesion (damage) and the resulting disorder(s) [97]. We have simulated brain damage at various locations and developed a brain pathology database with focal and distributed vascular [111], cranial nerve-related [112], and regional anatomy-related [113] synthesised lesions. Each lesion has been labelled with the resulting disorder and associated signs, symptoms, and/or syndromes (and additionally linked with relevant neurology textbook materials).

Mobile versions of the anatomic and neurologic disorders atlases also have been developed [98–100].

Finally, celebrating my 25th anniversary of brain atlasing work and 20th anniversary of the release of my first brain atlas product [117], I published two review papers [115, 116]. In [115], I gave an overview of mathematical methods as well as computational methods and tools in brain atlasing, sharing our contribution and experience about the methods devised and tools developed to create brain atlases and develop atlas-based applications. In [116], I presented the state of the art in brain atlasing and summarised my past and present efforts; shared my experience in atlas creation, validation, and commercialisation; compared our work with the state of the art; and proposed future directions, namely, to develop a disruptive, multilevel brain atlas platform with three directions: content spanning from molecules to behaviour; variability covering structure, function, and disorders; and time across the lifespan.

2.6 Summary

The brain contains the cerebrum, cerebellum, and brainstem, and it encases the ventricular system. The cerebrum comprises the paired cerebral hemispheres, diencephalon (with thalamus and hypothalamus), and deep grey matter nuclei, the main of them including the caudate nucleus, putamen, lateral and medial globus pallidus, hippocampus, and amygdala. The cerebral hemispheres are parcellated into the frontal, temporal, parietal, occipital, and limbic lobes. The cerebellum contains the paired cerebellar hemispheres united by the midline vermis. The brainstem is subdivided into the midbrain, pons, and medulla. The ventricular system contains the paired lateral and midline third and fourth ventricles.

The cerebral vasculature comprises the arterial and venous systems. The brain is supplied by two pairs of arteries: internal carotid arteries anteriorly and vertebral arteries posteriorly. The anterior and posterior circulations are connected by the circle of Willis, from which originate three paired branches: anterior cerebral, middle cerebral, and posterior cerebral arteries. The venous system contains the dural sinuses and cerebral superficial and deep veins.

The brain is connected by the commissural, association, and projection tracts. The main commissural tracts (interconnecting both hemispheres) are the corpus callosum and anterior and posterior commissures. The major association tracts (interconnecting different regions of the same hemisphere) are superior longitudinal, middle longitudinal, inferior longitudinal, superior occipito-frontal, inferior occipito-frontal, and uncinate fascicles. The main projection tracts (connecting the cortex with the subcortical structures) contain corticospinal, corticothalamic (including optic radiation), corticobulbar, and corticopontine tracts as well as auditory radiation.

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