Cerebrum Fiber Tracts

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ABSTRACT

BACKGROUND: The fiber tracts of the cerebrum may be a more important determinant of resection limits than the cortex. Better knowledge of the 3-dimensional (3-D) anatomic organization of the fiber pathways is important in planning safe and accurate surgery for lesions within the cerebrum.

OBJECTIVE: To examine the topographic anatomy of fiber tracts and subcortical gray matter of the human cerebrum and their relationships with consistent cortical, ventricular, and nuclear landmarks.

METHODS: Twenty-five formalin-fixed human brains and 4 whole cadaveric heads were examined by fiber dissection technique and ×6 to ×40 magnification. The fiber tracts and central core structures, including the insula and basal ganglia, were examined and their relationships captured in 3-D photography. The depth between the surface of the cortical gyri and selected fiber tracts was measured.

RESULTS: The topographic relationships of the important association, projection, and commissural fasciculi within the cerebrum and superficial cortical landmarks were identified. Important landmarks with consistent relationships to the fiber tracts were the cortical gyri and sulci, limiting sulci of the insula, nuclear masses in the central core, and lateral ventricles. The fiber tracts were also organized in a consistent pattern in relation to each other. The anatomic findings are briefly compared with functional data from clinicoradiological analysis and intraoperative stimulation of fiber tracts.

CONCLUSION: An understanding of the 3-D anatomic organization of the

fiber tracts of the brain is essential in planning safe and accurate cerebral surgery.

INTRODUCTION

Damage to the fiber tracts in the cerebrum may result in more severe and irreversible deficits than damage to the cortex.[1-4] There also appears to be a higher plasticity in cortical areas than subcortical ones. The subcortical fiber tracts (white matter) are not only important in maintaining cerebral connectivity, but are also an essential consideration in determining resection limits. As a result, fiber tracts play a major role in surgical planning, along with consideration of the cortex, arteries, and veins.[4]

The anatomic features of the fiber tracts of the cerebrum were examined in previous studies.[5-10] This study, using 3-dimensional (3-D) photography, focuses on the complicated spatial relationships of the fiber tracts and subcortical gray matter and their relationships with surface landmarks including the cortical gyri. These anatomic findings are briefly compared with functional data from clinicoradiological analysis and intraoperative stimulation of fiber tracts. However, the main focus is on 3-D anatomic relationships.

METHODS

Twenty-five formalin-fixed brains (50 hemispheres) and 4 whole cadaveric human heads were examined. The arachnoid and surface vessels were removed from the brains. All specimens were frozen at 216°C for 2 weeks.[11] After completion of the freezing process, the specimens were thawed, and the fiber tracts were dissected using microdissectors under ×6 to ×40 magnifications provided by a Zeiss Surgical Microscope (Carl Zeiss AG, Oberkochen, Germany). The specimens were stored in a 5% formalin solution between the dissection sessions. The fiber tracts in the cadaveric heads were examined via a frontotemporal craniotomy. The dissections were done in a stepwise manner. The position of the fiber tracts found in each deeper step of these dissections was noted according to their depth from the overlying cortical gyri. Proceeding laterally to medially, the central core structures between the insular cortex and the midline were examined.

During the exposure of the fiber tracts in stepwise dissections, measurements were taken from 10 brains (20 hemispheres) using electronic scales (Table 1). Each stage of the dissections was recorded with 3-D photography to prepare 3-D anaglyph images, as reported in a previous article from this laboratory.[12] The topographic location and depth of the subcortical fiber tracts in relation to the overlying gyrus or gyri, especially in the frontal lobe, were analyzed to provide surgically relevant 3-D images. Each 3-D image is displayed beside or above a corresponding labeled 2-dimensional image. The anaglyph images, to be viewed with red and blue glasses, were assembled using Adobe Photoshop CS5, Version 12.0X 64 (Adobe, San Jose, California). Anaglyph images on a printed page are best viewed with red and blue glasses when lying flat with good illumination; however, a well-lighted computer monitor with enlargement of the 3-D image provides much better viewing.

TABLE 1. Distance From the Surface of Gyrus to Tracts: 20 Hemispheres (in cm)[a]

Region	Tract	Average	Range	SD
Frontal lobe				
Superior frontal gyrus	Corona radiata (claustrocortical fibers in the posterior part of the gyrus + frontopontine + superior frontal thalamic radiations)	1.5	0.5-2.0	1.57
	Callosal fibers	2.0	1.0-3.0	0.20
	SLF I	2.2	1.3-4.0	0.70
Middle frontal gyrus	SLF II	2.0	1.0-2.5	0.57
	AF dorsal (posterior part of the gyrus)	2.5	2.0-3.0	0.52
	IFOF (mid part of the gyrus)	3.0	2.0-4.0	0.80
	Corona radiata (claustrocortical fibers + frontopontine + superior and anterior frontal thalamic radiations)	>3.0	—	—
	Callosal fibers	3.2	2.5-4.0	0.80
Inferior frontal gyrus	SLF III	1.0	0.5-1.5	0.23
	AF ventral and dorsal	1.5	1.0-2.0	0.52
	IFOF	3.0	2.5-4.0	0.97
	Corona radiata (claustrocortical + frontopontine + superior and anterior frontal thalamic radiations)	>3.0	—	—
Parietal lobe				
Superior parietal lobule	Corona radiata (claustrocortical fibers in the anterior part of the lobule + parietopontine + parietal thalamic radiations)	>3.0	—	—
	Callosal fibers	>3.0	—	—
	SLF I	3.5	3.5-4.0	0.20
Inferior parietal lobule	SLF III (anterior and ventral parts of the lobule)	1.0	0.5-1.5	0.23
	AF ventral and dorsal	2.0	1.0-3.0	0.30
	SLF II	2.2	2.0-4.0	0.63
	MdLF (posterior part of the lobule)	3.0	2.5-4.0	0.40
	IFOF (posterior part of the lobule)	3.0	2.5-4.0	0.40
	Corona radiata (claustrocortical fibers + parietopontine + parietal thalamic radiations)	>3.0	—	—
	Tapetum	4.0	3.5-5.0	0.40
Temporal lobe				
Superior temporal gyrus	MdLF	—	—	—
	AF ventral and dorsal (posterior part of the gyrus)	1.5	1.0-3.0	0.84
	UF (anterior part of the gyrus)	3.0	2.5-3.5	0.23
	IFOF	3.0	2.5-3.5	0.23
	Anterior commissure	>3.0	—	—
	Sagittal stratum (occipitopontine + temporopontine + optic radiations)	>3.0	—	—
	Tapetum	4.0	3.5-4.5	0.23
Middle temporal gyrus	AF ventral and dorsal (posterior part of the gyrus)	1.5	1.0-3.0	0.84
	IFOF	2.4	1.5-4.0	0.80
	UF (anterior part of the gyrus)	3.0	2.0-5.0	0.94
	Anterior commissure	3.0	2.0-5.0	1.05
	Sagittal stratum (occipitopontine + temporopontine + optic radiations)	>3.0	—	—
	Tapetum	3.3	3.0-6.0	0.94
Inferior temporal gyrus	AF dorsal (posterior part of the gyrus)	1.3	1.0-2.0	0.48
	ILF	1.3	0.5-2.0	0.53
Occipital lobe				
Superior occipital gyrus	ILF	2.5	2.0-3.0	0.52
	IFOF, anterior commissure, and sagittal stratum	>2.5	—	—
	Forceps major	3.0	2.5-4.0	0.40
	Cingulum (medial part of the gyrus)	>3.0	—	—
Middle occipital gyrus	SLF II (sometimes)	2.0	1.5-2.5	0.24
	ILF	2.5	2.0-3.0	0.23
	IFOF	3.3	3.0-4.0	0.42
	Anterior commissure, sagittal stratum, and tapetum	>3.5	—	—
Inferior occipital gyrus	ILF	2.5	2.0-3.0	0.52
	IFOF, anterior commissure, and sagittal stratum	>2.5	—	—
	Forceps major	3.0	2.5-4.0	0.40

[a]SD, standard deviation; SLF, superior longitudinal fasciculus; AF, arcuate fasciculus; IFOF, inferior fronto-occipital fasciculus; MdLF, middle longitudinal fasciculus; ILF, inferior longitudinal fasciculus.

RESULTS

Association Fibers

Removing the cortex of the cerebrum exposed the short association fibers, the so-called intergyral or U fibers, which interconnect neighboring gyri. Deep to the short association fibers are the long association fibers (Figure 1). Generally, the depth and length of the association fiber pathways are directly proportional; the longer association fibers that interconnect distant areas are positioned at a deeper (more medial) level than shorter ones.

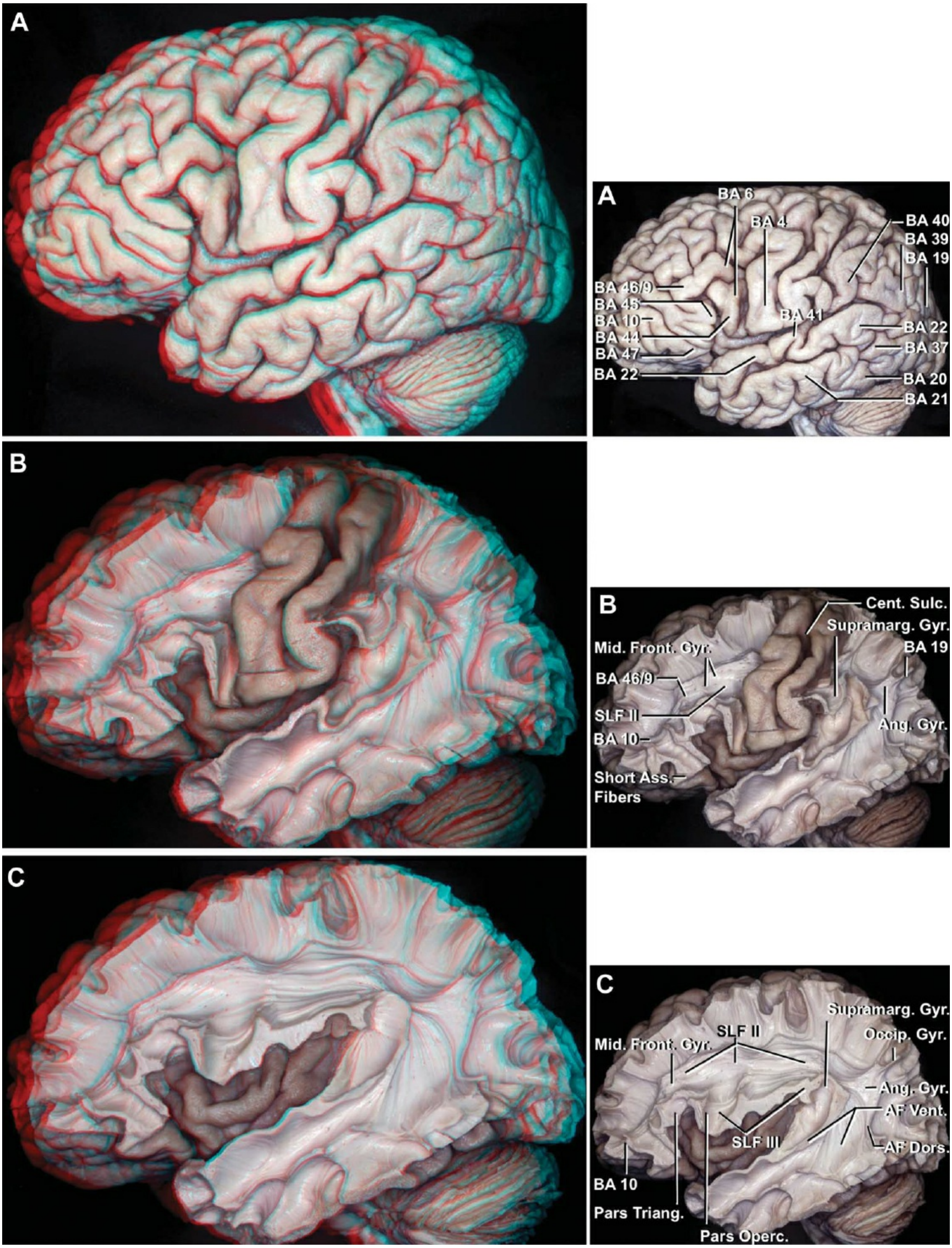


Figure 1 (A–C). Perisylvian and long association fibers. A, the perisylvian cortex is composed of the ventral premotor cortex (BA 6), the inferior frontal gyrus including the pars opercularis (BA 44), triangularis (BA 45), and orbitalis (BA 47), the middle frontal gyrus (BA 46/9), the inferior parietal lobule including the supramarginal (BA 40) and angular (BA 39) gyri, and the superior (BA 22, BA 41, and BA 42), middle (BA 21, BA 37),

and inferior temporal (BA 20) gyri. B, the central lobe, formed by the pre- and postcentral gyri, has been preserved. Removal of the cortex and adjacent short association fibers exposed the long association fibers. The cortex and short and long association fibers are positioned in order laterally to medially. The SLF II connects the angular gyrus (BA 39) or posterior part of the middle occipital gyrus (BA 19) to the middle frontal gyrus (BA 10 or BA 46/9) and courses deep to the anterior part of the middle occipital gyrus, the inferior parietal lobule, midlevel of the pre- and postcentral gyri, and middle frontal gyrus. C, the most superficial long association fibers are the SLF and AF. The SLF consists of frontoparietal connections and the AF of frontotemporal connections. The SLF II courses superficial to the upper part of the atrium and the body of the lateral ventricle. The ventral fiber pathway in the suprasylvian area is the SLF III, which connects the supramarginal gyrus to the pars opercularis. The AF is divided into ventral and dorsal segments. The ventral segment extends from the mid and posterior parts of the superior gyrus and mid part of the middle temporal gyrus, passes deep to the lower part of the supramarginal gyrus and medial to the SLF III in the frontoparietal operculum to reach the inferior frontal gyrus. The dorsal segment extends from the posterior part of the middle and inferior temporal gyri, passes through the angular gyrus and ventral to the SLF II to reach the inferior and middle frontal gyri. AF, arcuate fasciculus; Ang., angular; Ass., association; BA, Brodmann area; Cent., central; Dors., dorsal; Front., frontal; Gyr., gyrus; IFOF, inferior fronto-occipital fasciculus; ILF, inferior longitudinal fasciculus; Inf., inferior; Mid., middle; MdLF, middle longitudinal fasciculus; Occip., occipital; Operc., opercularis; PIP, posterior insular point; Preoccip., preoccipital; SLF, superior longitudinal fasciculus; Sulc., sulcus; Sup., superior; Supramarg., supramarginal; Temp., temporal; Triang., triangularis; Vent., ventral. (Images courtesy of AL Rhoton, Jr.)

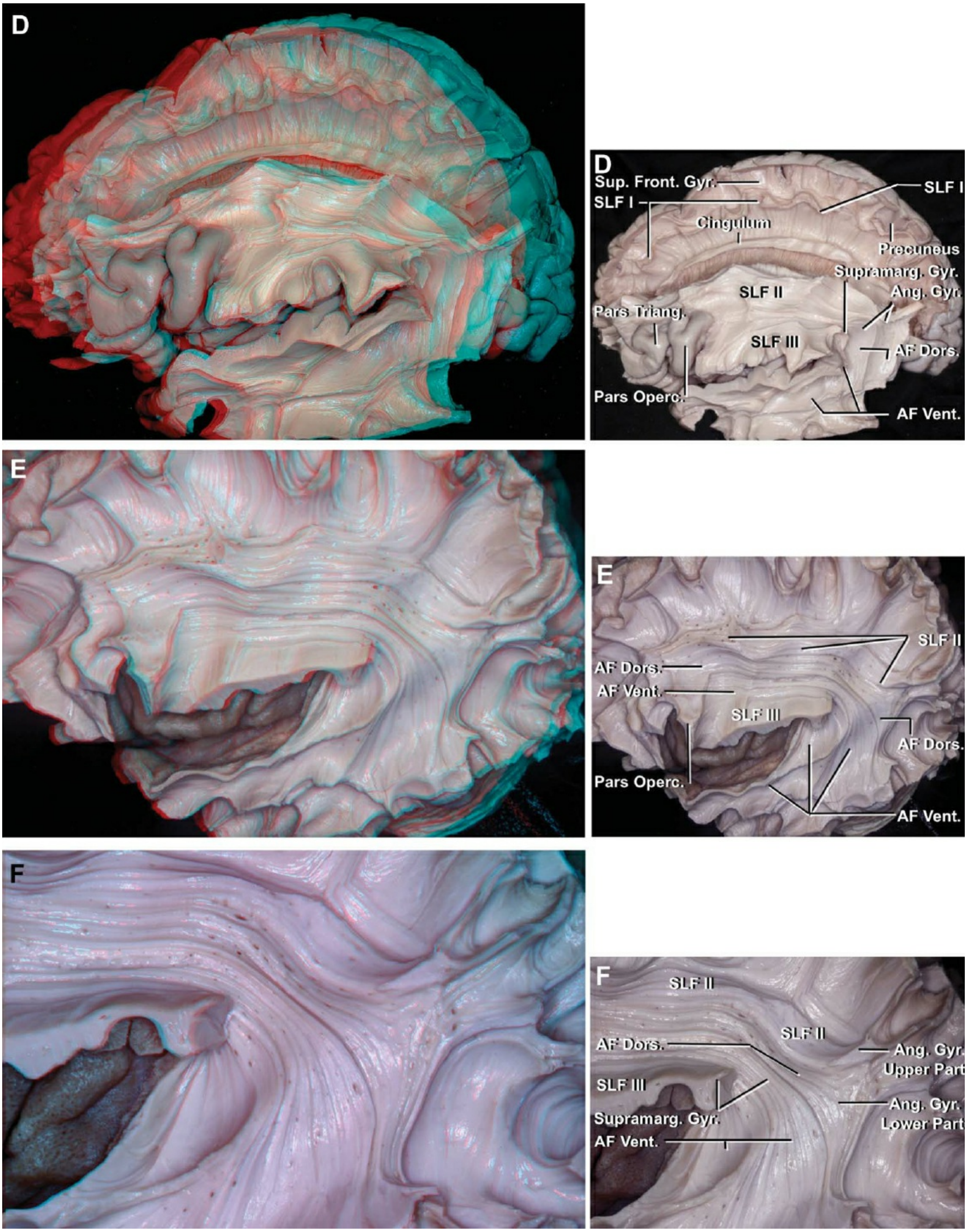


Figure 1 (D–F). D, The SLF I, II, and III and the temporal cortical areas of the AF segments have been exposed. The SLF I is exposed on the contralateral side because it is located in the medial part of the hemisphere. The SLF I courses within the upper bank of the cingulate sulcus above the cingulum and medial to the callosal fibers and connects the precuneus to the medial frontal gyrus and anterior cingulate cortex. The SLF III, SLF II, and SLF I are positioned in that order laterally to

medially and ventral to dorsal. E, relationship of the AF and SLF segments in the suprasylvian area. The AF ventral segment travels with and medial to the SLF III. The AF dorsal segment travels with and ventral to the SLF II. F, enlarged view of the inferior parietal lobule. The AF ventral segment passes through the supramarginal gyrus and projects forward with the SLF III in the frontoparietal operculum. The AF dorsal segment passes through the angular gyrus and projects forward just ventral to the SLF II. The AF dorsal segment passes through the lower part of the angular gyrus, whereas the SLF II passes through the upper part of the angular gyrus. AF, arcuate fasciculus; Ang., angular; Ass., association; BA, Brodmann area; Cent., central; Dors., dorsal; Front., frontal; Gyr., gyrus; IFOF, inferior fronto-occipital fasciculus; ILF, inferior longitudinal fasciculus; Inf., inferior; Mid., middle; MdLF, middle longitudinal fasciculus; Occip., occipital; Operc., opercularis; PIP, posterior insular point; Preoccip., preoccipital; SLF, superior longitudinal fasciculus; Sulc., sulcus; Sup., superior; Supramarg., supramarginal; Temp., temporal; Triang., triangularis; Vent., ventral. (Images courtesy of AL Rhoton, Jr.)

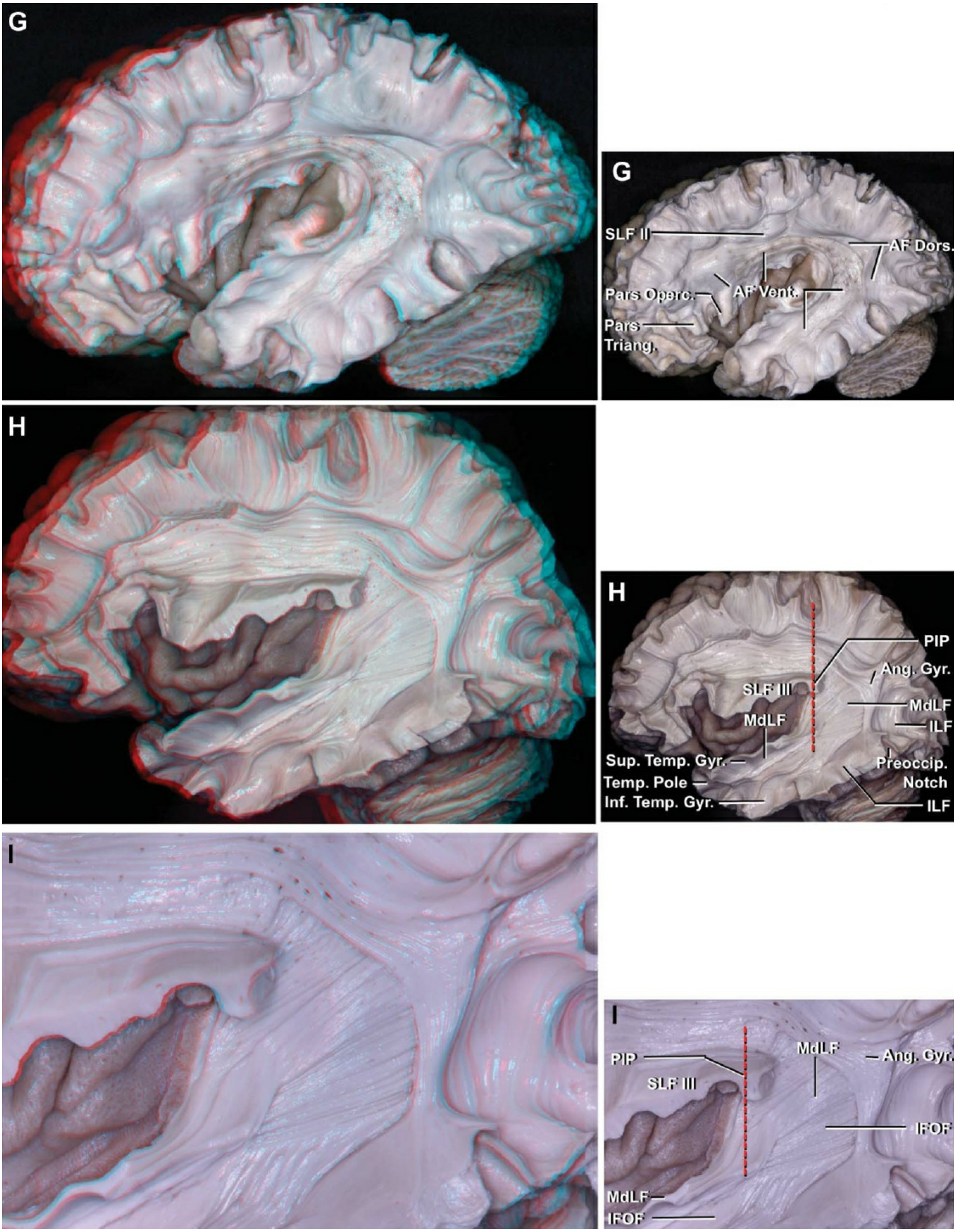


Figure 1 (G–I). G, the termination of the AF ventral segment at the pars triangularis and temporal lobe has been exposed. H, removal of all AF segments in the infrasylvian area exposes the MdLF and ILF. The MdLF begins in the temporal pole and passes through the superior temporal gyrus to reach the inferior parietal lobule, especially the angular gyrus. The MdLF can be divided into anterior and posterior parts at the

posterior insular point (interrupted red line), the junction of the superior and inferior limiting sulci. The anterior part of the MdLF, located anterior to the posterior insular point, courses superficial to the IFOF, whereas the posterior part of the MdLF is intermingled with the IFOF. The ILF connects the temporal pole and the dorsolateral occipital cortex without reaching the calcarine cortex. At the level of the preoccipital notch, it turns 45° upward to reach the dorsolateral occipital cortex. I, enlarged view of the MdLF. AF, arcuate fasciculus; Ang., angular; Ass., association; BA, Brodmann area; Cent., central; Dors., dorsal; Front., frontal; Gyr., gyrus; IFOF, inferior fronto-occipital fasciculus; ILF, inferior longitudinal fasciculus; Inf., inferior; Mid., middle; MdLF, middle longitudinal fasciculus; Occip., occipital; Operc., opercularis; PIP, posterior insular point; Preoccip., preoccipital; SLF, superior longitudinal fasciculus; Sulc., sulcus; Sup., superior; Supramarg., supramarginal; Temp., temporal; Triang., triangularis; Vent., ventral. (Images courtesy of AL Rhoton, Jr.)

The most superficial long association fibers are the superior longitudinal fasciculus (SLF) and arcuate fasciculus (AF). The SLF consists of frontoparietal connection fibers and the AF of frontotemporal connection fibers. The SLF has 3 parts: SLF I, II, and III. The SLF I is positioned within the superior frontal gyrus, SLF II within the middle frontal gyrus, and SLF III within the inferior frontal gyrus. Starting at the lateral surface and moving medially, the components of the SLF are encountered in reverse order: SLF III, SLF II, then SLF I (Figure 1).[13] The SLF I, the dorsal fiber pathway, lies within the upper bank of the cingulate sulcus, the precuneus (medial surface of the parietal lobe), and the medial surface of the superior frontal gyrus (medial frontal gyrus) and travels just above the cingulum and medial to the callosal fibers (Figure 1D).[9,13-15] One fiber dissection study reported the SLF I as a short association pathway; however, we found that the anterior portion of the SLF I is continuous with the posterior portion.[16] The long association fiber pathways located in the suprasylvian area take on a wavy configuration because of their deflection around the sulci on the convexity. The same wavy appearance is seen in the SLF II. The SLF I is regarded as relevant to higher order control of body-centered action and the initiation of motor activity.[13,17,18] The SLF

II, the middle pathway, courses between the angular and middle frontal gyri at the level of the upper edge of the atrium and the body of the lateral ventricle. Functionally, the SLF II is related to regulation of spatial awareness.[13] In turn, damage to the SLF II may result in disorders of spatial working memory and attention such as neglect syndrome.[14,19] Direct electrical inhibition of the SLF II during surgery causes a transient decrease in the appreciation of visual stimuli on the contralateral side.[14,19] The ventral fiber pathway coursing within the frontoparietal operculum is the SLF III, which connects the supramarginal gyrus to the pars opercularis.[13] Functionally, the left (dominant) SLF III is involved in phonological processing (working memory).[13,20,21] Stimulation of the left SLF III produces articulatory disorders such as dysarthria/anarthria.[13,20,21] The right (nondominant) SLF III, however, is involved in visuospatial attention, prosody, and music processing.[13,14,22-24]

Another superficial long association fiber pathway is the AF, which connects the motor (Broca's area) and sensory (Wernicke's area) language centers. The AF is divided into ventral and dorsal segments (Figure 1). The ventral segment is ventral to the dorsal segment in the suprasylvian area but is anterior to the dorsal segment in the infrasylvian area. The ventral segment passes from the mid and posterior parts of the superior temporal gyrus and mid part of the middle temporal gyrus through the lower part of the supramarginal gyrus and medial to the SLF III in the frontoparietal operculum to reach the inferior frontal gyrus. The dorsal segment passes from the posterior part of the middle and inferior temporal gyri through the lower part of the angular gyrus and then travels slightly ventrally to the SLF II to reach the inferior and middle frontal gyri. Based on our dissections and the literature from neuroimaging, lesion task–based, and diffusion tensor imaging (DTI) studies, the AF ventral segment is associated with phonological language processing, whereas the AF dorsal segment is associated with lexical and semantic language processing. The ventral segment of the AF is equivalent to the classic AF model.[25,26]

In the infrasylvian area, the main long association fiber pathways are the middle and inferior longitudinal fasciculi (MdLF and ILF) (Figures 1H and

1I). The MdLF lies within the superior temporal gyrus and the ILF within the inferior temporal gyrus. The MdLF originates from the temporal pole and passes through the superior temporal gyrus to reach the inferior parietal lobule, especially the angular gyrus. The MdLF was first described by Seltzer and Pandya[27] using an autoradiography technique on the macaque monkey. Their findings first adapted to the human brain showed the MdLF in the human brain with DTI.[28]

The MdLF can be divided into anterior and posterior parts at the level of the posterior insular point, the junction of the superior and inferior limiting sulci, and posteromedial end of the anterior transverse temporal (Heschl's) gyrus. The anterior part of the MdLF courses superficial to the inferior frontooccipital fasciculus (IFOF), whereas the posterior part of the MdLF is intermingled with the IFOF.[29] It is not possible using either fiber dissection technique or imaging to distinguish the MdLF fibers from the IFOF and sagittal stratum fibers behind the angular gyrus, contrary to some previously reported studies about termination of the MdLF in the occipital lobe.[30,31]

The function of the MdLF is still unclear. Makris et al[28] suggested that the MdLF may play an important role in language and attention. However, De Witt Hamer et al[29] did not find any language disturbance after resection and electrostimulation of the anterior part of the MdLF in 8 patients. Hence, they concluded that the anterior part of the MdLF is not related to language processing. There are no data regarding the posterior part of the MdLF, but it has been suggested that it is involved in the location of sound because it courses between the angular gyrus, which is a part of the navigation center of the brain, and the auditory reception area on Heschl's gyrus.[31]

The inferior longitudinal fasciculus (ILF) connects the temporal pole to the dorsolateral occipital cortex without reaching the calcarine cortex (Figures 1H, 2G, and 2K). At the level of the preoccipital notch, it bends upward at a 45° angle to be distributed to the dorsolateral occipital cortex. A DTI study revealed that the ILF is an occipitotemporal connection that has short and long association fibers originating in the extrastriate areas, with rostral terminations in the middle and inferior temporal gyri, temporal pole, parahippocampal gyrus, hippocampus, and amygdala (also called the amygdaloid body).[32] The ILF is involved in object identification and recognition.[17,33] Although intraoperative stimulation of the ILF did not elicit any language disturbance, the ILF has been proposed as an indirect semantic language pathway because of its connections in the areas involved in semantic and syntactic processing such as the fusiform (occipitotemporal) gyrus and temporal pole.[34] It has also been suggested that the ILF plays a role in language comprehension, together with the MdLF and extreme capsule, as part of the ventral semantic pathway.[35,36] The ILF is located below the axial level of the temporal horn of the lateral ventricle. Resection of the inferior temporal gyrus and underlying ILF, even in the dominant hemisphere, does not result in major deficits.[6]

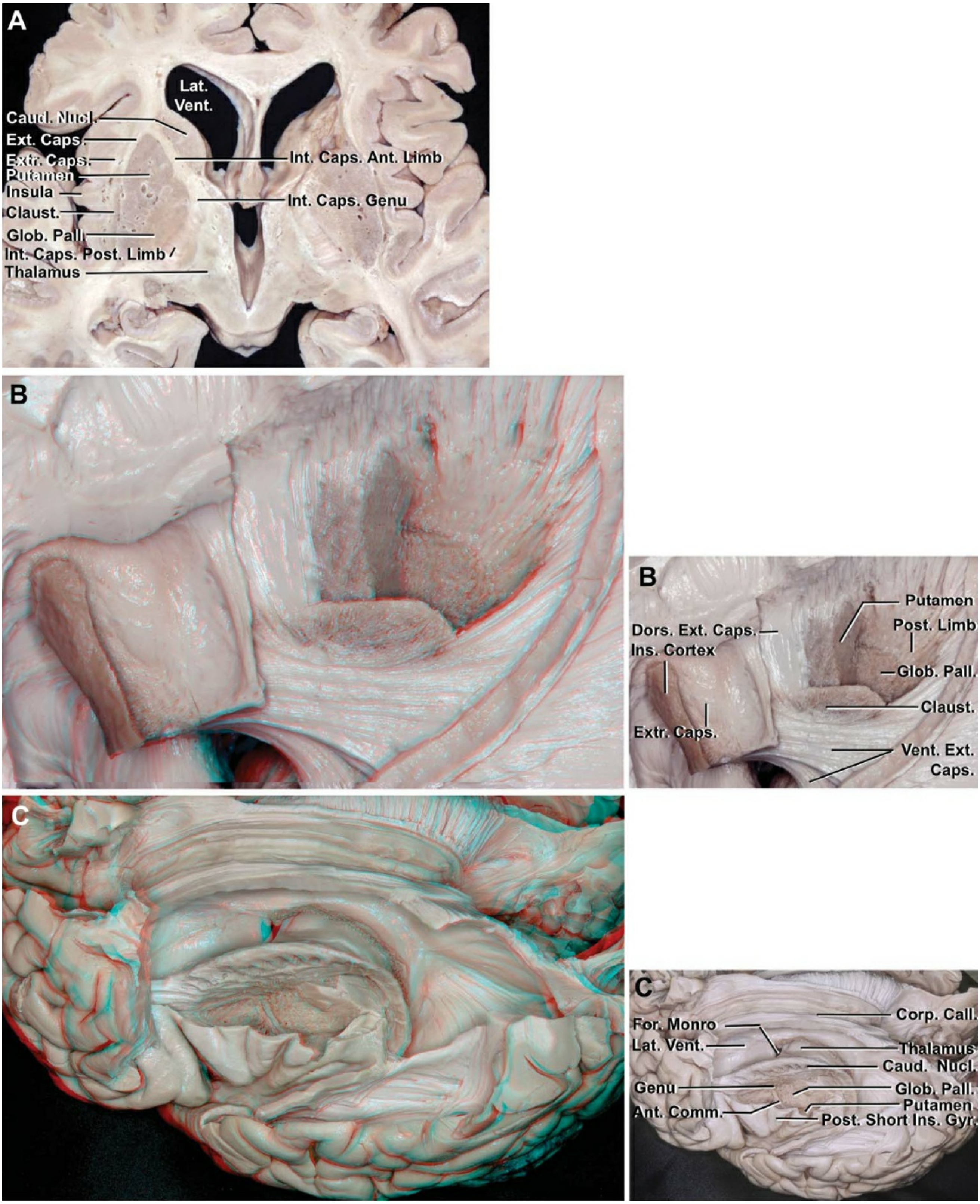


Figure 2 (A–C). A, axial section through the central core of the cerebrum. The central core area is located between the insular cortex laterally and the ventricles medially. The central core includes the insular cortex, extreme capsule, claustrum and external capsule, putamen, globus pallidus, internal capsule, caudate nucleus, and thalamus. B, laterally to medially, the central core structures exposed include the insular cortex, extreme capsule, claustrum, ventral and dorsal parts of the external capsule, the putamen, globus pallidus, and posterior limb of the internal

capsule. C, superolateral view of the central core structures. The caudate nucleus, globus pallidus, and thalamus have been exposed. The insular cortex forms the lateral border of the central core, and the lateral ventricle above and third ventricle below form the medial border. The genu of the internal capsule is located just behind the anterior commissure and at the same coronal plane as the posterior short insular gyrus and foramen of Monro. Acc., accumbens; AIP, anterior insular point; Amyg., amygdala; Ant., anterior; Call., callosal, callosum.; Caps., capsule; Caud., caudate; Cent., central, centrum; Claust., claustrum; Claustrocort., claustrocortical; CN, cranial nerve; Comm., commissure; Cor., corona; Corp., corpus; Dia., diagonal; Dors., dorsal; Dorsolat., dorsolateral; Ext., extension, external; Extr., extreme; FLP, frontal limen point; For., foramen; Front., frontal; Gl., gland; Glob., globus; Gyr., gyrus; Hippo., hippocampus; Hypoth., hypothalamus; IFOF, inferior fronto-occipital fasciculus; ILF, inferior longitudinal fasciculus; Inf., inferior; Innom., innominata; Ins., insula, insular; Int., internal; Lat., lateral; Lent., lenticular; LGB, lateral geniculate body; Lim., limiting; Mam., mammillary, mammillo; Med., medial, medullaris; MLF, medial longitudinal fasciculus; Nucl., nucleus; Occip., occipital; Orb. Front., orbitofrontal; Pall., pallidus; Par., parietal, parieto; PIP, posterior insular point; Post., posterior; Rad., radiata, radiations; Sag., sagittal; Sept., septal; SLF, superior longitudinal fasciculus; Str., stria; Strat., stratum; Subst., substantia; Subthal., subthalamic; Sulc., sulcus; Sup., superior; Temp., temporal; Thal., thalami, thalamic; TLP, temporal limen point; Tr., tract; UF, uncinate fasciculus; Vent., ventral, ventricle; Ventromed., ventromedial. (Images courtesy of AL Rhoton, Jr.)

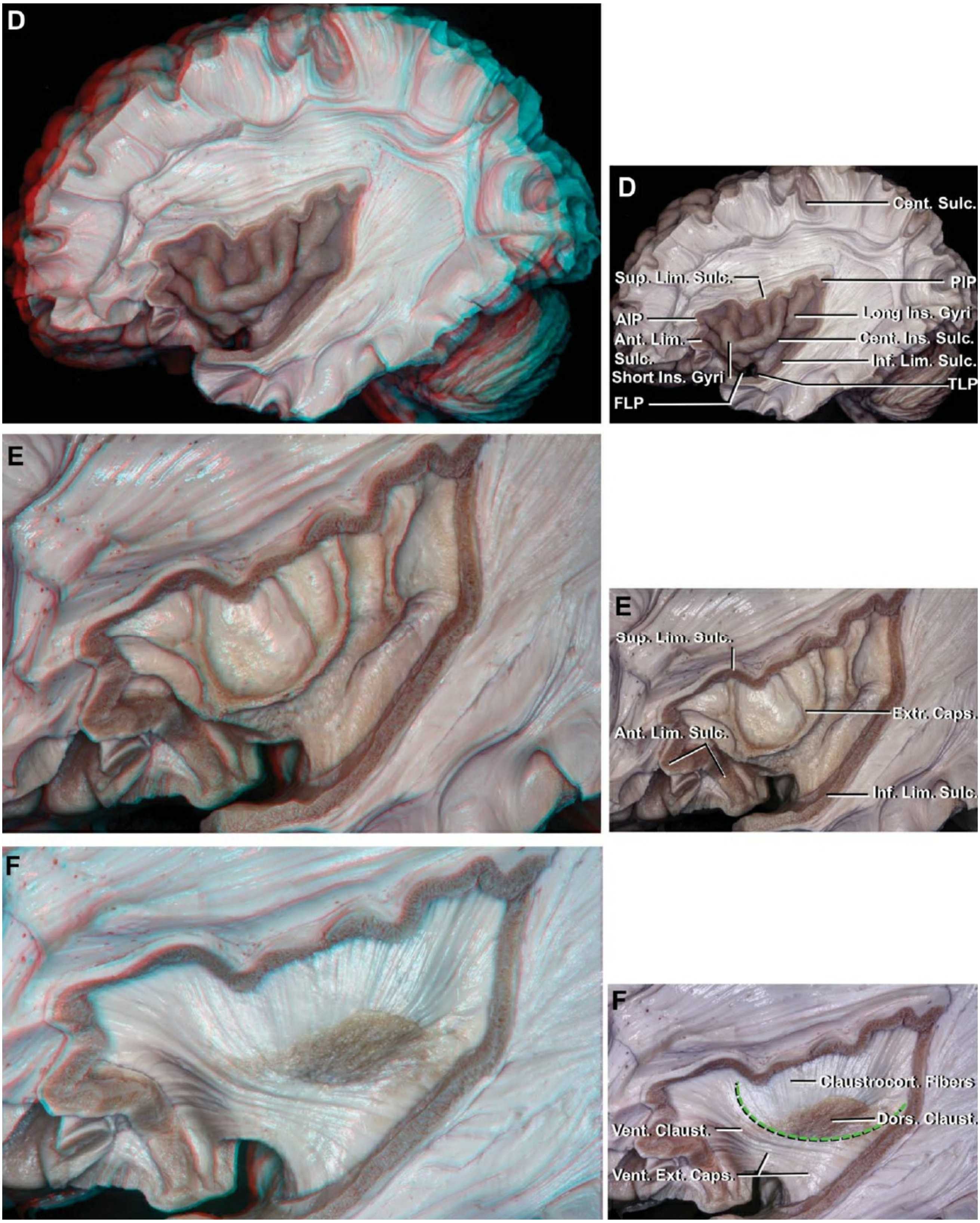


Figure 2 (D–F). D, the frontoparietal and temporal opercula have been removed to expose the insula. The central insular sulcus courses deep to and almost parallel with the central sulcus on the convexity and divides the insular cortex into short and long insular gyri. The insula is encircled by the superior, inferior, and anterior limiting sulci. The junction of the anterior and superior limiting sulci is referred to as the anterior insular point, and the junction of the superior and inferior limiting sulci is

referred to as the posterior insular point. Two additional important points are the temporal and frontal limen points, located at the junctions of the inferior and anterior limiting sulci with the limen insulae, respectively. E, removing the insular cortex exposes the extreme capsule, which is composed of short association fibers and provides connections between the insular gyri and the opercular areas. F, removing the extreme capsule exposes the external capsule and claustrum. The external capsule and claustrum are divided into ventral and dorsal parts. The dorsal external capsule is formed by the claustrocortical fibers, connecting the cortex and dorsal claustrum reciprocally. The dorsal claustrum is located between the extreme and external capsules. The ventral claustrum is formed by scattered clumps of gray matter in the ventral external capsule that reach the amygdala. The green interrupted line marks the border between the ventral and dorsal external capsule. Acc., accumbens; AIP, anterior insular point; Amyg., amygdala; Ant., anterior; Call., callosal, callosum.; Caps., capsule; Caud., caudate; Cent., central, centrum; Claust., claustrum; Claustrocort., claustrocortical; CN, cranial nerve; Comm., commissure; Cor., corona; Corp., corpus; Dia., diagonal; Dors., dorsal; Dorsolat., dorsolateral; Ext., extension, external; Extr., extreme; FLP, frontal limen point; For., foramen; Front., frontal; Gl., gland; Glob., globus; Gyr., gyrus; Hippo., hippocampus; Hypoth., hypothalamus; IFOF, inferior fronto-occipital fasciculus; ILF, inferior longitudinal fasciculus; Inf., inferior; Innom., innominata; Ins., insula, insular; Int., internal; Lat., lateral; Lent., lenticular; LGB, lateral geniculate body; Lim., limiting; Mam., mammillary, mammillo; Med., medial, medullaris; MLF, medial longitudinal fasciculus; Nucl., nucleus; Occip., occipital; Orb. Front., orbitofrontal; Pall., pallidus; Par., parietal, parieto; PIP, posterior insular point; Post., posterior; Rad., radiata, radiations; Sag., sagittal; Sept., septal; SLF, superior longitudinal fasciculus; Str., stria; Strat., stratum; Subst., substantia; Subthal., subthalamic; Sulc., sulcus; Sup., superior; Temp., temporal; Thal., thalami, thalamic; TLP, temporal limen point; Tr., tract; UF, uncinate fasciculus; Vent., ventral, ventricle; Ventromed., ventromedial. (Images courtesy of AL Rhoton, Jr.)

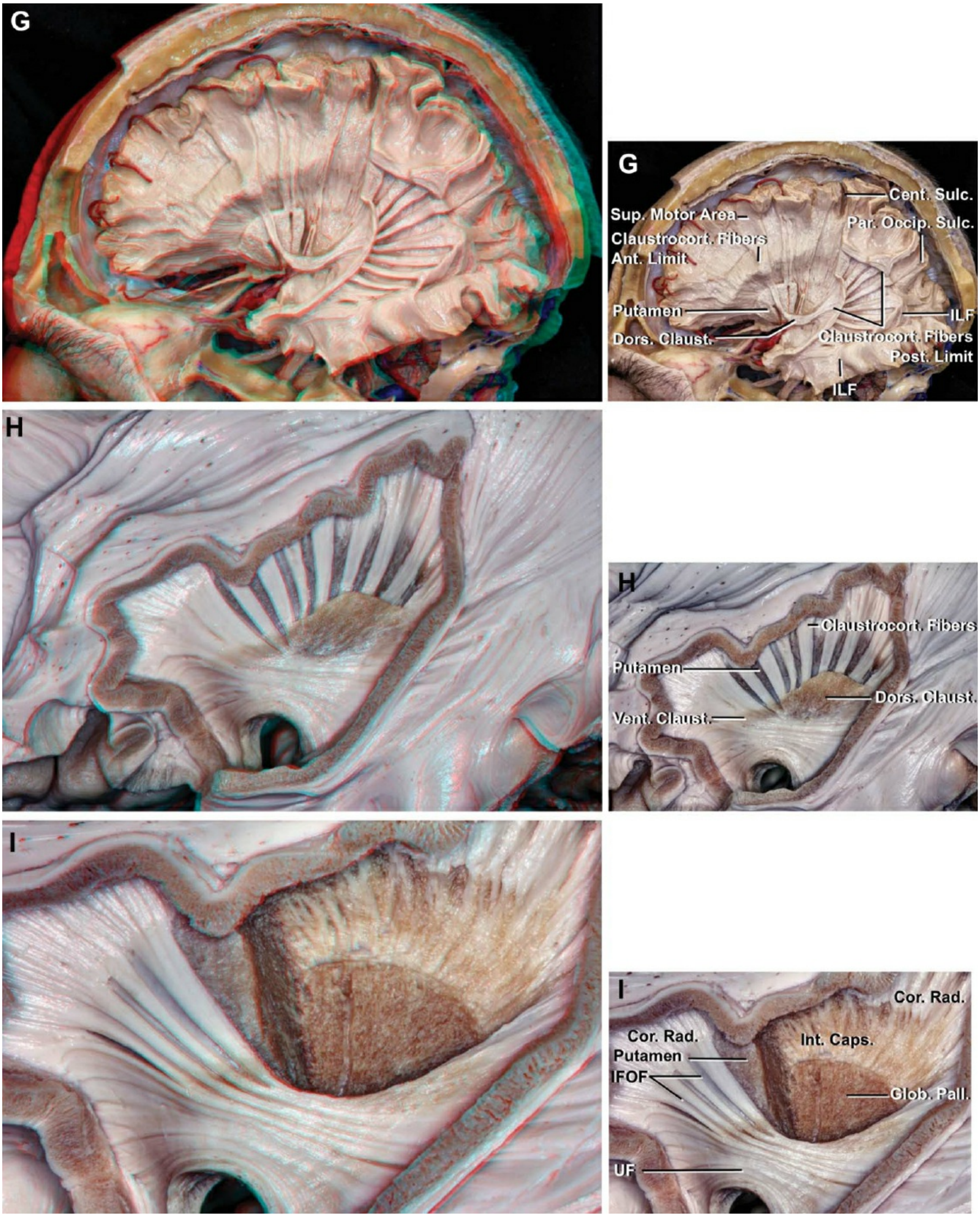


Figure 2 (G–I). G, the dorsal external capsule and claustrocortical fibers interconnect the dorsal claustrum and the cortex between the supplementary motor area anteriorly and the posterior part of the parietal lobe posteriorly. At the level of the preoccipital notch, the ILF can be seen bending upward at a 45° angle. H, some bands of claustrocortical fibers have been removed to expose the putamen. I, the posterior half of the putamen has been removed to expose the globus

pallidus and internal capsule. The globus pallidus, located just medial to the putamen, is lighter in color than the putamen. The external capsule, located lateral to the putamen, and the internal capsule, located medial to the putamen and globus pallidus, come together above the putamen to form the corona radiata. The external capsule is formed by the IFOF and UF. Acc., accumbens; AIP, anterior insular point; Amyg., amygdala; Ant., anterior; Call., callosal, callosum.; Caps., capsule; Caud., caudate; Cent., central, centrum; Claust., claustrum; Claustrocort., claustrocortical; CN, cranial nerve; Comm., commissure; Cor., corona; Corp., corpus; Dia., diagonal; Dors., dorsal; Dorsolat., dorsolateral; Ext., extension, external; Extr., extreme; FLP, frontal limen point; For., foramen; Front., frontal; Gl., gland; Glob., globus; Gyr., gyrus; Hippo., hippocampus; Hypoth., hypothalamus; IFOF, inferior fronto-occipital fasciculus; ILF, inferior longitudinal fasciculus; Inf., inferior; Innom., innominata; Ins., insula, insular; Int., internal; Lat., lateral; Lent., lenticular; LGB, lateral geniculate body; Lim., limiting; Mam., mammillary, mammillo; Med., medial, medullaris; MLF, medial longitudinal fasciculus; Nucl., nucleus; Occip., occipital; Orb. Front., orbitofrontal; Pall., pallidus; Par., parietal, parieto; PIP, posterior insular point; Post., posterior; Rad., radiata, radiations; Sag., sagittal; Sept., septal; SLF, superior longitudinal fasciculus; Str., stria; Strat., stratum; Subst., substantia; Subthal., subthalamic; Sulc., sulcus; Sup., superior; Temp., temporal; Thal., thalami, thalamic; TLP, temporal limen point; Tr., tract; UF, uncinate fasciculus; Vent., ventral, ventricle; Ventromed., ventromedial. (Images courtesy of AL Rhoton, Jr.)

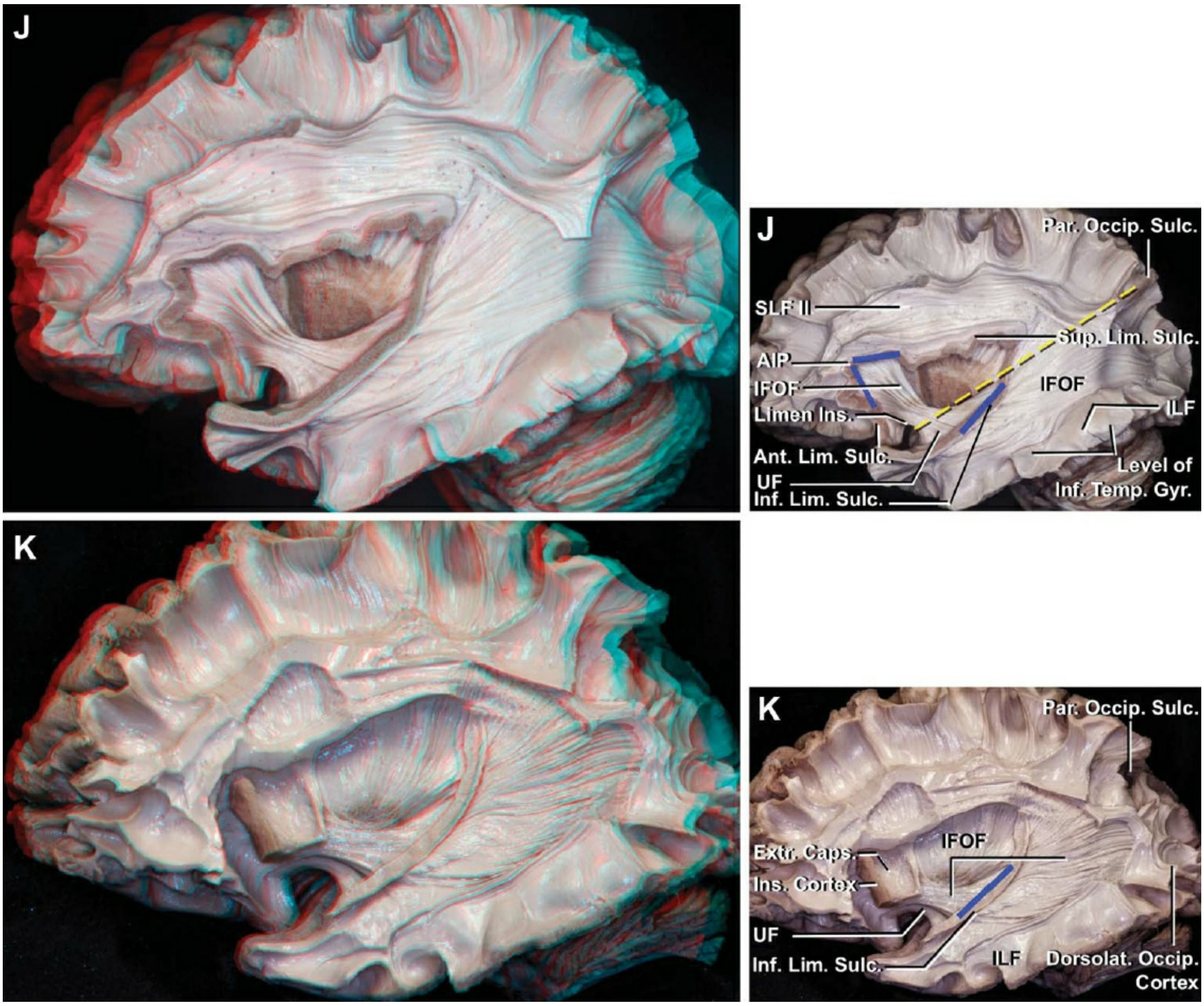


Figure 2 (J–K). J, the IFOF courses between the frontal and the parietal and occipital lobes. At the level of the middle frontal gyrus, the IFOF travels lateral to the corona radiata and medial to the SLF II, and passes deep to the anterior third of the superior limiting sulcus (blue line) and the superior half of the anterior limiting sulcus (blue line). Its fibers narrow just above the UF at the level of the limen insulae, pass deep to the middle third of the inferior limiting sulcus (blue line), and course backward within the superior and middle temporal gyri to reach the posterior part of the parietal and the occipital lobes. After passing deep to the inferior limiting sulcus, the upper limit of the cortical distribution of the IFOF at the parieto-occipital cortex is along a line (broken yellow line) connecting the midpoint of the anterior edge of the limen insulae and the upper end of the parieto-occipital sulcus. This line is also the border between the dorsal (claustrocortical fibers) and ventral (IFOF) external capsule. The UF passes deep to the inferior half of the anterior limiting sulcus and most anterior part of the inferior limiting sulcus and

connects the orbitofrontal and septal areas to the temporal pole. The ILF has been exposed at the level of the inferior temporal gyrus. K, another specimen. The separation of the IFOF and UF is shown. The IFOF and UF are positioned deeper than the extreme capsule in the central core area. The IFOF passes deep to the middle third of the inferior limiting sulcus (blue line) to reach the occipital lobe while the UF courses deep to the most anterior part of the inferior limiting sulcus to reach the temporal pole. The ILF passes deep to the inferior temporal gyrus and dorsolateral occipital cortex. Acc., accumbens; AIP, anterior insular point; Amyg., amygdala; Ant., anterior; Call., callosal, callosum.; Caps., capsule; Caud., caudate; Cent., central, centrum; Claust., claustrum; Claustrocort., claustrocortical; CN, cranial nerve; Comm., commissure; Cor., corona; Corp., corpus; Dia., diagonal; Dors., dorsal; Dorsolat., dorsolateral; Ext., extension, external; Extr., extreme; FLP, frontal limen point; For., foramen; Front., frontal; Gl., gland; Glob., globus; Gyr., gyrus; Hippo., hippocampus; Hypoth., hypothalamus; IFOF, inferior fronto-occipital fasciculus; ILF, inferior longitudinal fasciculus; Inf., inferior; Innom., innominata; Ins., insula, insular; Int., internal; Lat., lateral; Lent., lenticular; LGB, lateral geniculate body; Lim., limiting; Mam., mammillary, mammillo; Med., medial, medullaris; MLF, medial longitudinal fasciculus; Nucl., nucleus; Occip., occipital; Orb. Front., orbitofrontal; Pall., pallidus; Par., parietal, parieto; PIP, posterior insular point; Post., posterior; Rad., radiata, radiations; Sag., sagittal; Sept., septal; SLF, superior longitudinal fasciculus; Str., stria; Strat., stratum; Subst., substantia; Subthal., subthalamic; Sulc., sulcus; Sup., superior; Temp., temporal; Thal., thalami, thalamic; TLP, temporal limen point; Tr., tract; UF, uncinate fasciculus; Vent., ventral, ventricle; Ventromed., ventromedial. (Images courtesy of AL Rhoton, Jr.)

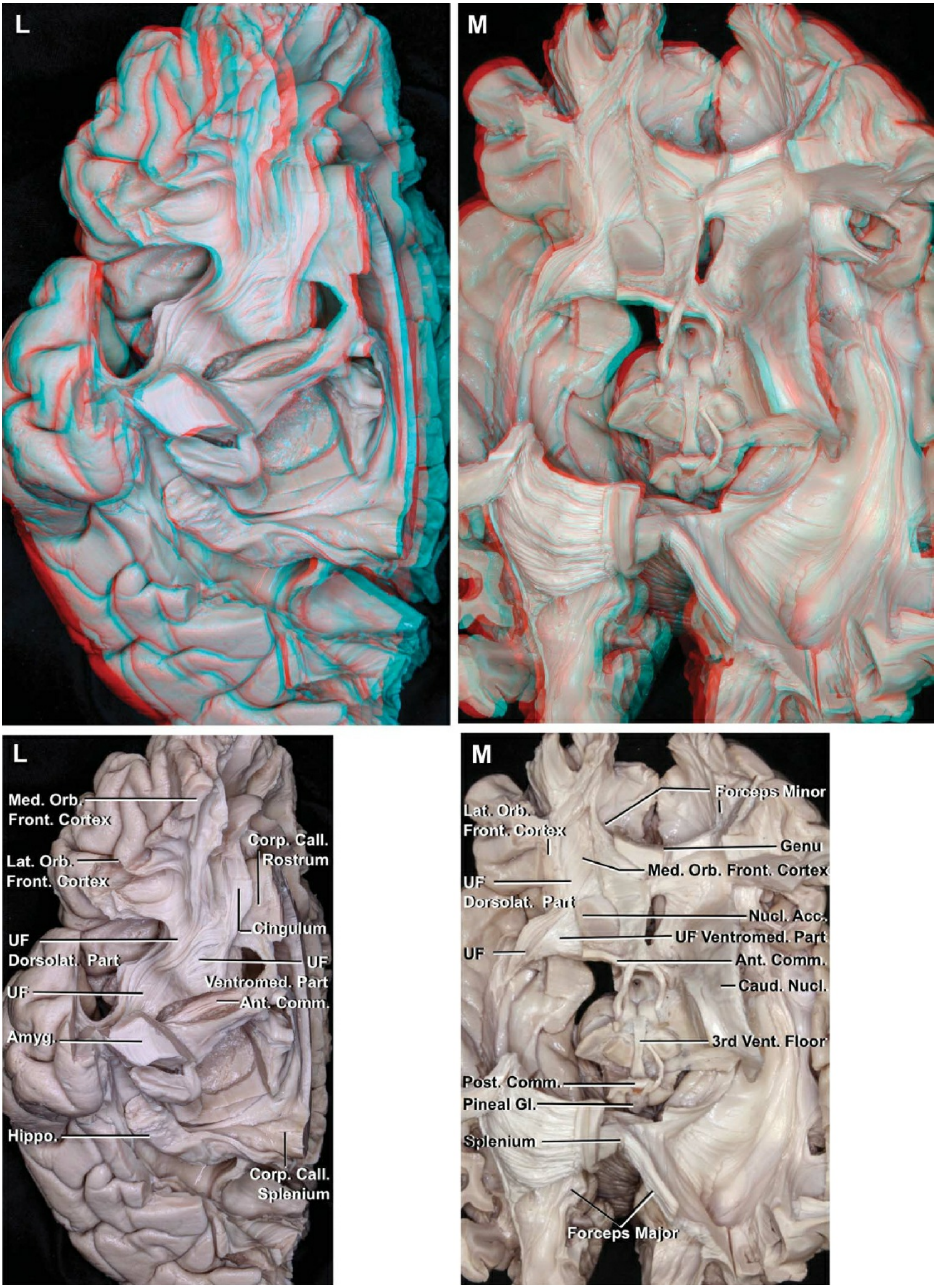


Figure 2 (L–M). L, inferior view of the 2 parts of the UF. The dorsolateral part projects to the lateral orbitofrontal area, and the ventromedial part projects to the nucleus accumbens, and septal and medial orbitofrontal areas. The ventromedial part covers the inferior and medial walls of the

nucleus accumbens and meets the cingulum in the cortical area below the genu of the corpus callosum. M, superior view of the commissural fibers and dorsolateral and ventromedial parts of the UF. The ventromedial part connects the nucleus accumbens to the orbitofrontal area. The nucleus accumbens is located below the head of the caudate nucleus. The commissural fibers are the anterior commissure, which forms part of the anterior wall of the third ventricle, and the corpus callosum. The posterior commissure is located on the dorsal aspect of the upper end of the cerebral aqueduct. The callosal fibers crossing in the genu, called the forceps minor, turn forward to interconnect the frontal regions. The fibers crossing in the splenium, called the forceps major, turn posteriorly to interconnect the parieto-occipital regions. Acc., accumbens; AIP, anterior insular point; Amyg., amygdala; Ant., anterior; Call., callosal, callosum.; Caps., capsule; Caud., caudate; Cent., central, centrum; Claust., claustrum; Claustrocort., claustrocortical; CN, cranial nerve; Comm., commissure; Cor., corona; Corp., corpus; Dia., diagonal; Dors., dorsal; Dorsolat., dorsolateral; Ext., extension, external; Extr., extreme; FLP, frontal limen point; For., foramen; Front., frontal; Gl., gland; Glob., globus; Gyr., gyrus; Hippo., hippocampus; Hypoth., hypothalamus; IFOF, inferior fronto-occipital fasciculus; ILF, inferior longitudinal fasciculus; Inf., inferior; Innom., innominata; Ins., insula, insular; Int., internal; Lat., lateral; Lent., lenticular; LGB, lateral geniculate body; Lim., limiting; Mam., mammillary, mammillo; Med., medial, medullaris; MLF, medial longitudinal fasciculus; Nucl., nucleus; Occip., occipital; Orb. Front., orbitofrontal; Pall., pallidus; Par., parietal, parieto; PIP, posterior insular point; Post., posterior; Rad., radiata, radiations; Sag., sagittal; Sept., septal; SLF, superior longitudinal fasciculus; Str., stria; Strat., stratum; Subst., substantia; Subthal., subthalamic; Sulc., sulcus; Sup., superior; Temp., temporal; Thal., thalami, thalamic; TLP, temporal limen point; Tr., tract; UF, uncinate fasciculus; Vent., ventral, ventricle; Ventromed., ventromedial. (Images courtesy of AL Rhoton, Jr.)

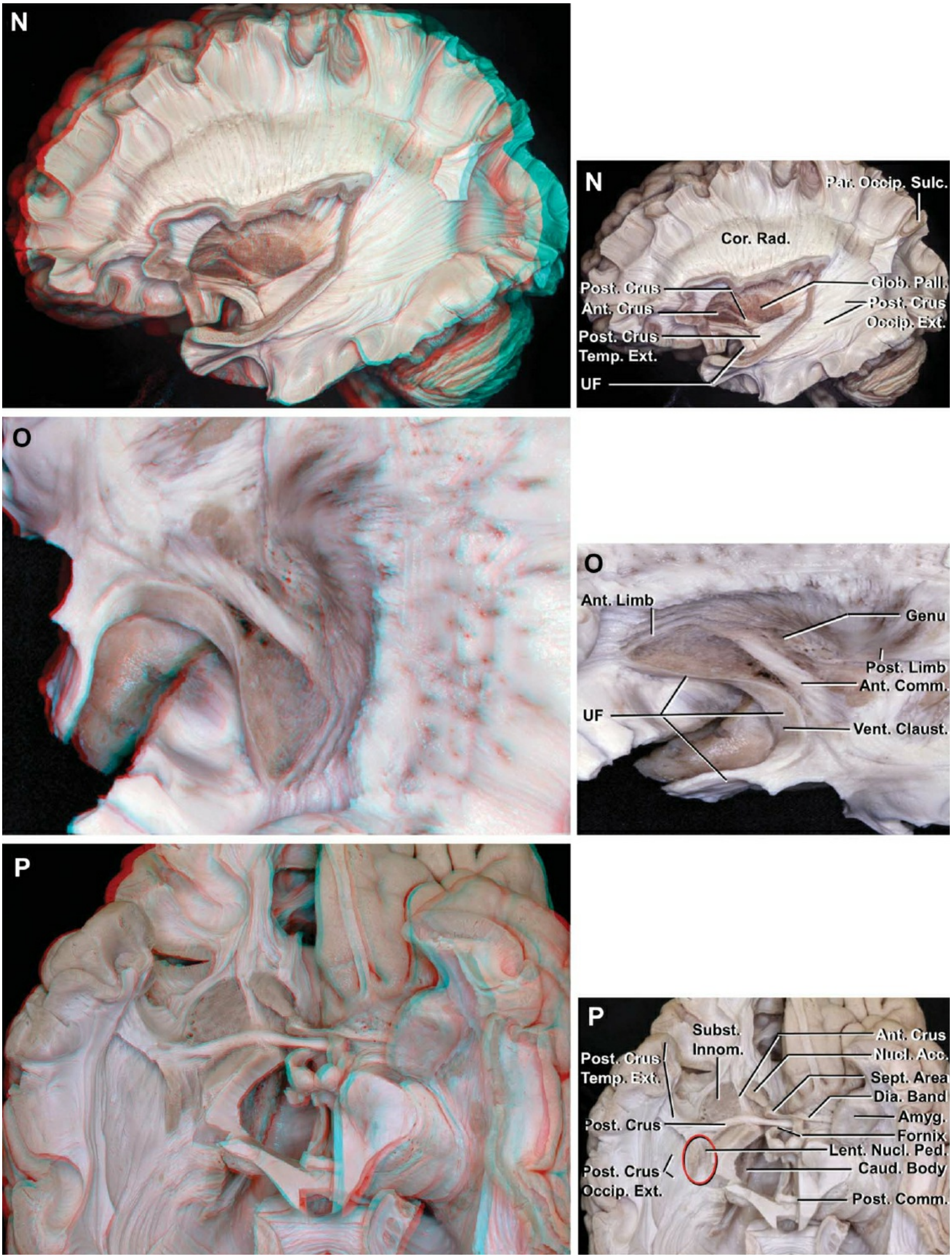


Figure 2 (N–P). N, lateral view. Removal of the IFOF and putamen exposes the anterior commissure and globus pallidus. The anterior commissure courses below the anterior limb of the internal capsule and gives rise to an anterior crus, which projects to the orbitofrontal area and olfactory nucleus. The posterior crus of the anterior commissure is directed caudally and laterally through the ventral aspect of the globus

pallidus in Gratiolet's canal and has temporal and occipital extensions. The temporal extension courses downward to the temporal pole and amygdala just behind the UF, and the occipital extension passes backward to the occipital lobe. O, the posterior crus of the anterior commissure runs laterally within Gratiolet's canal and undergoes torsion, so that its upper fibers descend along the medial side of the commissure to reach the temporal lobe, and the lower fibers ascend along the lateral side of the commissure to reach the occipital lobe. The internal capsule undergoes torsion in the same direction as the anterior commissure, placing the lower part of the posterior limb further lateral than the anterior limb. P, inferior view. The lentiform nucleus is joined to the amygdala by an inferior extension of the lentiform nucleus referred to as the peduncle of the lentiform nucleus. The anterior commissure resembles bicycle handlebars located immediately in front of the columns of the fornix and forms part of the anterior wall of the third ventricle. The temporal and occipital extensions of the posterior crus are exposed. Structures that sit below and anterior to the anterior commissure include the substantia innominata, nuclei accumbens and basalis, diagonal band of Broca, and medial septal nuclei. The substantia innominata is located lateral to the anterior crus of the anterior commissure and anterior limb of the internal capsule. The nucleus accumbens is situated medial to the anterior crus of the anterior commissure and anterior limb of the internal capsule, and below the level of posterior crus of the anterior commissure. The septal area is located in front of the anterior commissure next to the midline. Acc., accumbens; AIP, anterior insular point; Amyg., amygdala; Ant., anterior; Call., callosal, callosum.; Caps., capsule; Caud., caudate; Cent., central, centrum; Claust., claustrum; Claustrocort., claustrocortical; CN, cranial nerve; Comm., commissure; Cor., corona; Corp., corpus; Dia., diagonal; Dors., dorsal; Dorsolat., dorsolateral; Ext., extension, external; Extr., extreme; FLP, frontal limen point; For., foramen; Front., frontal; Gl., gland; Glob., globus; Gyr., gyrus; Hippo., hippocampus; Hypoth., hypothalamus; IFOF, inferior fronto-occipital fasciculus; ILF, inferior longitudinal fasciculus; Inf., inferior; Innom., innominata; Ins., insula, insular; Int., internal; Lat., lateral; Lent., lenticular; LGB, lateral geniculate body; Lim., limiting; Mam., mammillary, mammillo; Med., medial, medullaris; MLF, medial longitudinal fasciculus; Nucl., nucleus; Occip., occipital; Orb. Front., orbitofrontal; Pall., pallidus; Par., parietal, parieto; PIP, posterior insular point; Post., posterior; Rad., radiata, radiations; Sag., sagittal; Sept., septal; SLF, superior longitudinal fasciculus; Str., stria; Strat., stratum; Subst., substantia; Subthal., subthalamic; Sulc., sulcus; Sup., superior; Temp., temporal; Thal., thalami, thalamic; TLP, temporal limen point; Tr., tract; UF, uncinate fasciculus; Vent., ventral, ventricle; Ventromed., ventromedial. (Images courtesy of AL Rhoton, Jr.)

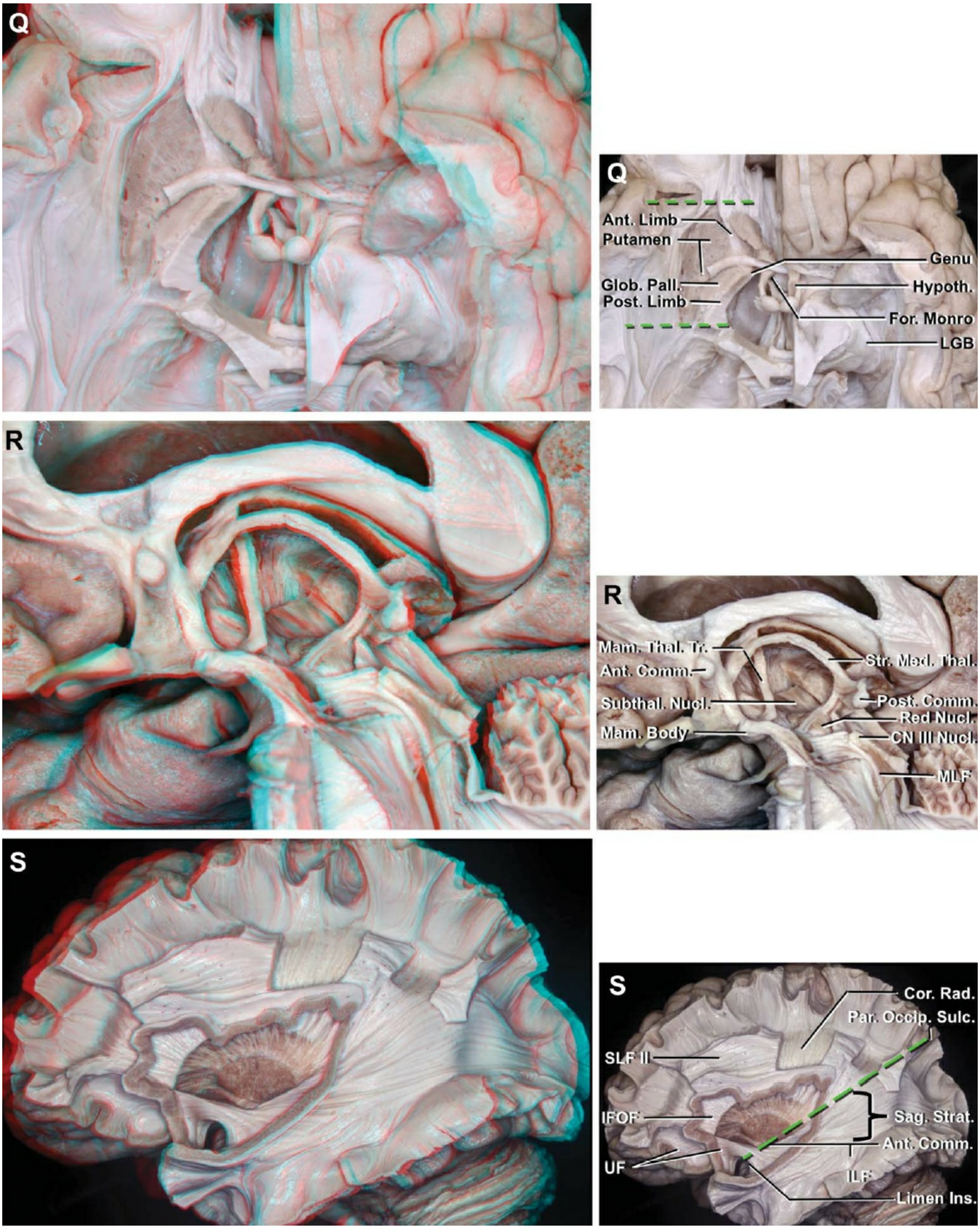


Figure 2 (Q–S). Q, inferior view. The anterior crus and the occipital and temporal extensions of the posterior crus of the anterior commissure have been removed. The genu of the internal capsule is positioned just behind the anterior commissure. The interrupted green lines mark the anterior and posterior borders of the internal capsule. The genu of the internal capsule and foramen of Monro are in the same coronal plane. The inferior limit of the parts of the internal capsule are the anterior

commissure for the anterior limb, the hypothalamus for the genu, and the lateral geniculate body for the posterior limb. R, medial view of the anterior and posterior commissures. The posterior commissure originates from the nucleus of the posterior commissure, which sits in front of the oculomotor nucleus. S, the frontoparietal projection fibers called the corona radiata are formed by the internal and external capsules and are positioned medial to the SLF II. The occipital and temporal projection fibers, called the sagittal stratum, are positioned medial to the occipital extension of the anterior commissure and the IFOF and ILF. The border between the corona radiata and sagittal stratum is positioned at a line (broken line) connecting the upper end of the parieto-occipital sulcus and the midpoint of the anterior edge of the limen insulae. The sagittal stratum is composed of occipitothalamic fibers, also called the optic radiations, and temporo- and occipitopontine fibers. Acc., accumbens; AIP, anterior insular point; Amyg., amygdala; Ant., anterior; Call., callosal, callosum.; Caps., capsule; Caud., caudate; Cent., central, centrum; Claust., claustrum; Claustrocort., claustrocortical; CN, cranial nerve; Comm., commissure; Cor., corona; Corp., corpus; Dia., diagonal; Dors., dorsal; Dorsolat., dorsolateral; Ext., extension, external; Extr., extreme; FLP, frontal limen point; For., foramen; Front., frontal; Gl., gland; Glob., globus; Gyr., gyrus; Hippo., hippocampus; Hypoth., hypothalamus; IFOF, inferior fronto-occipital fasciculus; ILF, inferior longitudinal fasciculus; Inf., inferior; Innom., innominata; Ins., insula, insular; Int., internal; Lat., lateral; Lent., lenticular; LGB, lateral geniculate body; Lim., limiting; Mam., mammillary, mammillo; Med., medial, medullaris; MLF, medial longitudinal fasciculus; Nucl., nucleus; Occip., occipital; Orb. Front., orbitofrontal; Pall., pallidus; Par., parietal, parieto; PIP, posterior insular point; Post., posterior; Rad., radiata, radiations; Sag., sagittal; Sept., septal; SLF, superior longitudinal fasciculus; Str., stria; Strat., stratum; Subst., substantia; Subthal., subthalamic; Sulc., sulcus; Sup., superior; Temp., temporal; Thal., thalami, thalamic; TLP, temporal limen point; Tr., tract; UF, uncinate fasciculus; Vent., ventral, ventricle; Ventromed., ventromedial. (Images courtesy of AL Rhoton, Jr.)

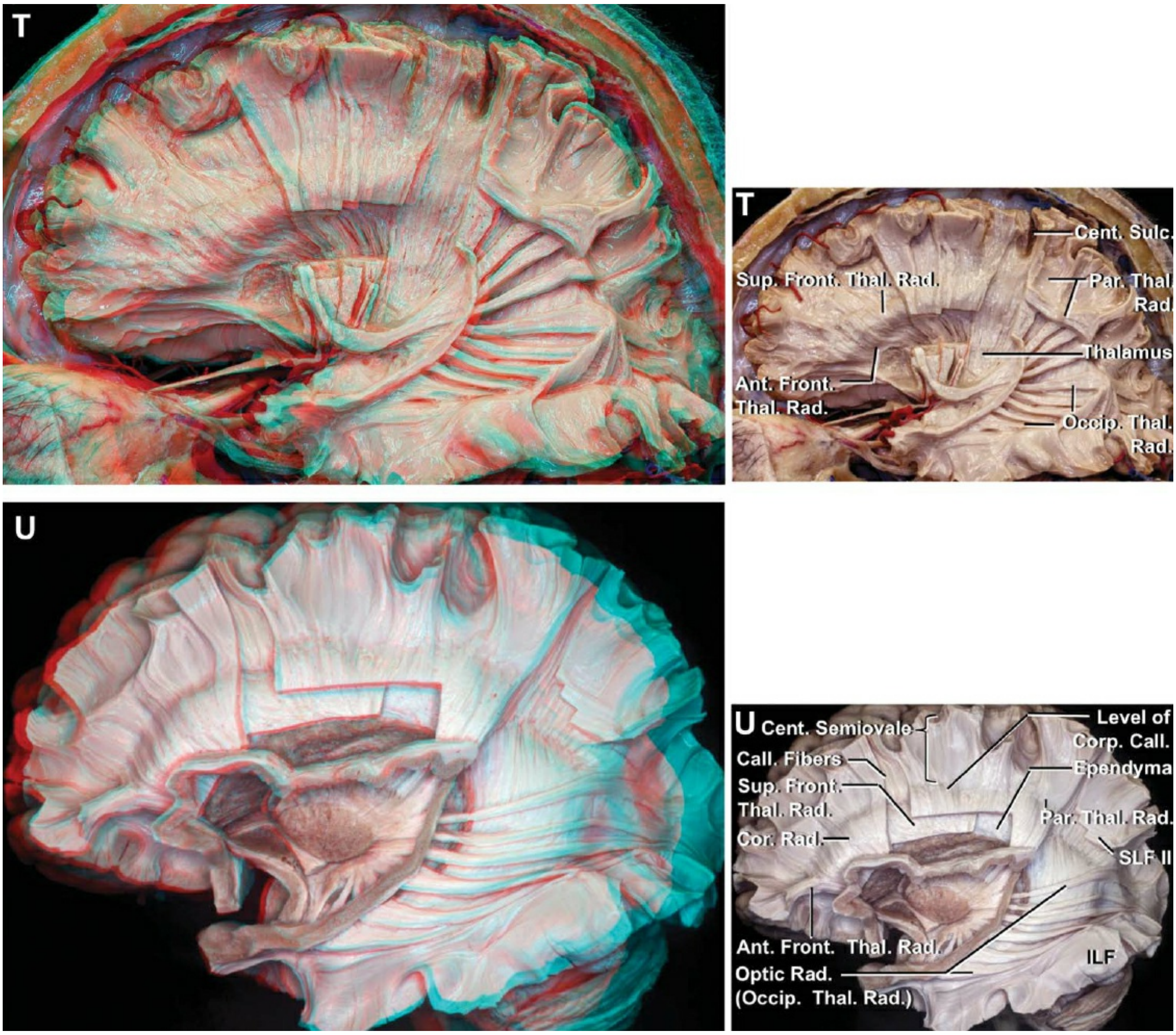
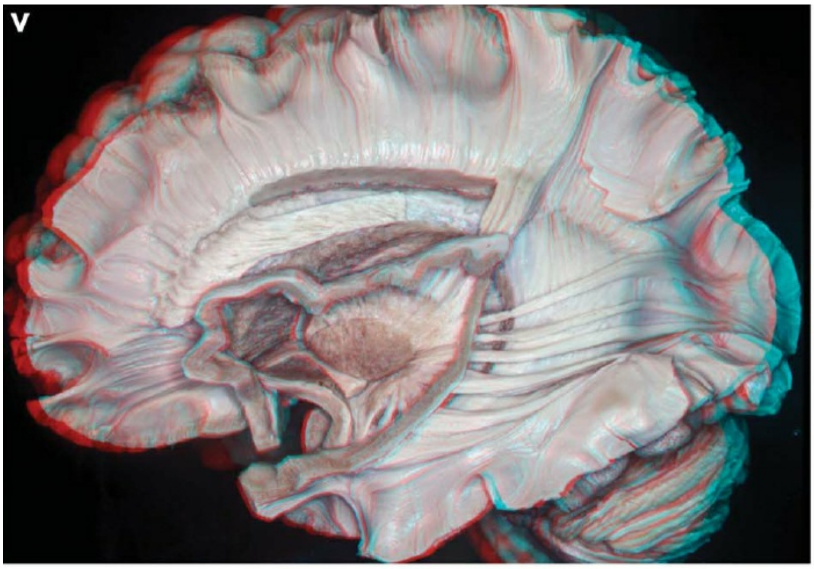
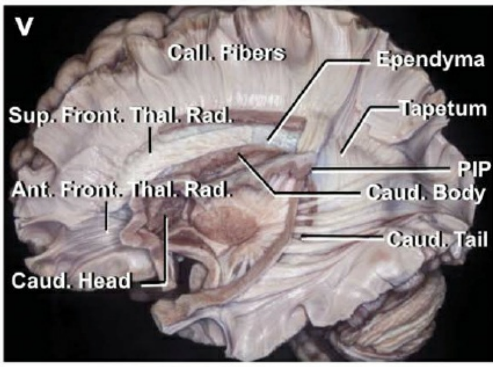
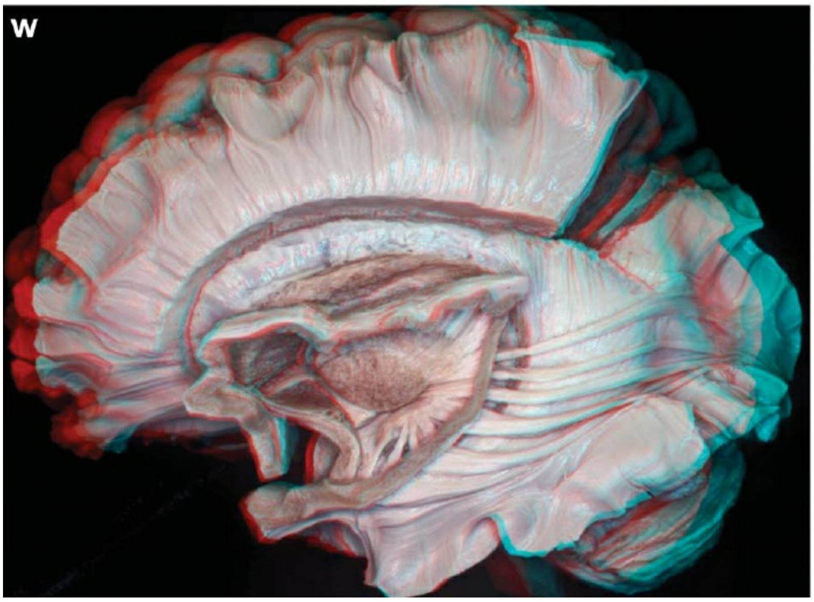


Figure 2 (T–U). T, compared with G, some of the claustrocortical fibers and internal capsule have been removed to expose the thalamic radiations connecting different parts of the cortex and thalamus. The anterior frontal and occipital thalamic radiations course horizontally. The superior frontal and parietal thalamic radiations course obliquely upward from their thalamic end. U, compared with S, the IFOF and occipital extension of the anterior commissure have been removed to expose the sagittal stratum. The centrum semiovale is located above at the level of the corpus callosum and consists of the SLF II association, corona radiata projection, and callosal fibers. Acc., accumbens; AIP, anterior insular point; Amyg., amygdala; Ant., anterior; Call., callosal, callosum.; Caps., capsule; Caud., caudate; Cent., central, centrum; Claust., claustrum; Claustrocort., claustrocortical; CN, cranial nerve; Comm., commissure; Cor., corona; Corp., corpus; Dia., diagonal; Dors., dorsal; Dorsolat., dorsolateral; Ext., extension, external; Extr., extreme; FLP, frontal limen

point; For., foramen; Front., frontal; Gl., gland; Glob., globus; Gyr., gyrus; Hippo., hippocampus; Hypoth., hypothalamus; IFOF, inferior fronto-occipital fasciculus; ILF, inferior longitudinal fasciculus; Inf., inferior; Innom., innominata; Ins., insula, insular; Int., internal; Lat., lateral; Lent., lenticular; LGB, lateral geniculate body; Lim., limiting; Mam., mammillary, mammillo; Med., medial, medullaris; MLF, medial longitudinal fasciculus; Nucl., nucleus; Occip., occipital; Orb. Front., orbitofrontal; Pall., pallidus; Par., parietal, parieto; PIP, posterior insular point; Post., posterior; Rad., radiata, radiations; Sag., sagittal; Sept., septal; SLF, superior longitudinal fasciculus; Str., stria; Strat., stratum; Subst., substantia; Subthal., subthalamic; Sulc., sulcus; Sup., superior; Temp., temporal; Thal., thalami, thalamic; TLP, temporal limen point; Tr., tract; UF, uncinate fasciculus; Vent., ventral, ventricle; Ventromed., ventromedial. (Images courtesy of AL Rhoton, Jr.)







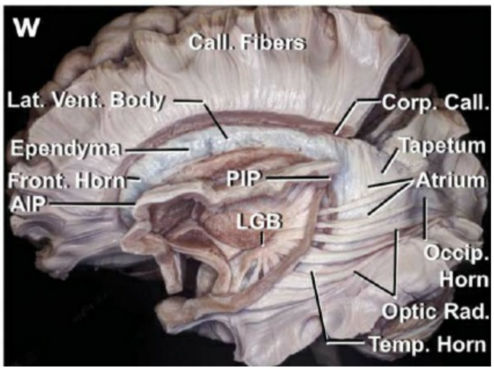


Figure 2 (V–W). V, the anterior frontal thalamic radiations, connecting the thalamus and the prefrontal cortex and frontal pole, course horizontally in the internal capsule. The superior frontal thalamic radiations, connecting the thalamus and medial frontal area and anterior portion of the cingulate gyrus, pass just lateral to the ependyma of the lateral ventricle and are the most medial fibers in the internal capsule. The tapetal fibers crossing in the splenium descend to separate the optic radiations from the lateral wall of the atrium and temporal and occipital horns of the lateral ventricle. W, removal of the corona radiata exposes the ependyma of the frontal horn and body of the lateral ventricle. The tapetal fibers, which cross in the splenium, course along the roof and lateral wall of the atrium and temporal and occipital horns of the lateral ventricle. The optic radiations arise from the lateral geniculate body and course in the roof and lateral wall of the temporal horn and lateral wall of the atrium and occipital horn of the lateral ventricle to reach the calcarine sulcus. The anterior insular point is positioned lateral to the frontal horn of the lateral ventricle, and the posterior insular point is positioned at the junction of the body and atrium. Acc., accumbens; AIP, anterior insular point; Amyg., amygdala; Ant., anterior; Call., callosal, callosum.; Caps., capsule; Caud., caudate; Cent., central, centrum; Claust., claustrum; Claustrocort., claustrocortical; CN, cranial nerve; Comm., commissure; Cor., corona; Corp., corpus; Dia., diagonal; Dors., dorsal; Dorsolat., dorsolateral; Ext., extension, external; Extr., extreme; FLP, frontal limen point; For., foramen; Front., frontal; Gl., gland; Glob., globus; Gyr., gyrus; Hippo., hippocampus; Hypoth., hypothalamus; IFOF, inferior fronto-occipital fasciculus; ILF, inferior longitudinal fasciculus; Inf., inferior; Innom., innominata; Ins., insula, insular; Int., internal; Lat., lateral; Lent., lenticular; LGB, lateral geniculate body; Lim., limiting; Mam., mammillary, mammillo; Med., medial, medullaris; MLF, medial longitudinal fasciculus; Nucl., nucleus; Occip., occipital; Orb. Front., orbitofrontal; Pall., pallidus; Par., parietal, parieto; PIP, posterior insular point; Post., posterior; Rad., radiata, radiations; Sag., sagittal; Sept., septal; SLF, superior longitudinal fasciculus; Str., stria; Strat., stratum; Subst., substantia; Subthal., subthalamic; Sulc., sulcus; Sup., superior; Temp., temporal; Thal., thalami, thalamic; TLP, temporal limen point; Tr.,

tract; UF, uncinate fasciculus; Vent., ventral, ventricle; Ventromed., ventromedial. (Images courtesy of AL Rhoton, Jr.)

Central Core

The central core of the cerebrum is located between the insular cortex laterally and ventricles medially. This area includes the extreme capsule, claustrum, external capsule, lentiform (putamen + globus pallidus) and caudate nucleus, internal capsule, basal forebrain, and thalamus (Figure 2).[37]

The first structure encountered in the central core, moving laterally to medially, is the insular cortex (Figures 2A-2D). The insula is encircled by the limiting (circular) sulcus and separated from the frontal, parietal, and temporal opercula by the anterior, superior, and inferior limiting sulci, which surround the insula in a triangle shape.[37] The 3 limiting insular sulci and 4 points along their junction provide important landmarks in insular surgery because they are easily found after splitting the sylvian fissure. These landmarks are the anterior and posterior insular points and frontal and temporal limen points. The anterior insular point is located at the junction of the anterior and superior limiting sulci and the posterior insular point is positioned at the junction of the superior and inferior limiting sulci.[38] Two additional important points are the temporal and frontal limen points, located at the junctions of the limen insulae with the inferior and anterior limiting sulci, respectively.

Another important orienting landmark is the central insular sulcus, which courses deep and almost parallel to the central sulcus on the convexity and divides the insular cortex into short and long insular gyri (Figure 2D). The short insular gyri are located anterior to the central insular sulcus and the long insular gyri are located posterior to the central insular sulcus.[37] The posterior short insular gyrus is positioned lateral to and in the same coronal plane as the genu of the internal capsule and interventricular foramen of Monro (Figure 2C).

Structures positioned from superficial to deep, medial to the pars triangularis of the inferior frontal gyrus, are the anterior insular point, IFOF, corona radiata fibers from the anterior limb of the internal capsule, and frontal horn of the lateral ventricle. The structures, positioned medial to the posterior insular point, are, from superficial to deep, the external capsule, corona radiata fibers from the posterior limb of the internal capsule, the tail of the caudate nucleus, and the junction of the body and atrium of the lateral ventricle. The posteromedial edge of Heschl's gyrus is located at the posterior insular point. The limiting sulci, the anterior and posterior insular and frontal and temporal limen points, are the most consistent surgical landmarks for planning insular surgery (Figure 2D).[38]

Removing the insular cortex exposes the extreme capsule, which connects the adjacent insular gyri horizontally and projects vertically, deep to the limiting sulci, to the opercular areas (Figure 2E). It has been suggested that the extreme capsule is composed of short association fibers connecting adjacent insular gyri.[39] Experimental studies of lesions in nonhuman primates show the short association fibers passing along the extreme capsule to connect the frontal, temporal, and parietal lobes.[40] To the contrary, autoradiography studies in macaque monkeys and several DTI studies in humans have suggested that the extreme capsule is a long association fiber pathway that connects the occipital and frontal lobes.[17,35,40] These fiber pathways have also been described as corresponding to the IFOF in humans because the IFOF does not exist in the macaque monkey. It has been suggested that the extreme capsule may participate in syntactic processing and ventral semantic functions of language usually attributed to the adjacent IFOF and uncinate fasciculus (UF).[41] The anatomy and function of the extreme capsule are still debated. In fiber dissection studies, it appears that the extreme capsule contains short association fibers that connect the insular gyri to each other and to the frontoparietal and temporal opercula.

Removing the extreme capsule exposes the claustrum and external capsule (Figure 2F). The claustrum is the thin collection of gray matter between the extreme capsule laterally and the external capsule medially. Both the external capsule and claustrum have 2 parts: ventral and dorsal.[8]

The dorsal external capsule is formed by claustrocortical projection fibers, which connect the claustrum and the cortex between the supplementary motor area anteriorly and posterior part of the parietal lobe posteriorly (Figures 2F-2H). The claustrocortical system is involved in the integration of visual, somatosensory, and motor information.[8] Bilateral injury of this system has resulted in severe encephalopathy.[8] The dorsal claustrum is located between the extreme and external capsules. The ventral external capsule is formed by the IFOF above and UF below. The ventral claustrum is formed by islands of gray matter interspersed in the ventral external capsule that extend laterally to the amygdala (Figures 2H and 2I).

The IFOF, which is a fronto-occipital association fiber pathway, connects the middle and inferior frontal gyri to the posterior part of the parietal and occipital lobes (Figures 2I-2K). In the frontal lobe, it reaches the dorsolateral prefrontal cortex (mid part of the middle frontal gyrus), pars orbitalis, and pars triangularis. The IFOF is located lateral (superficial) to the corona radiata fibers and medial (deep) to the SLF II and AF segments in the frontal lobe. The IFOF passes deep to the anterior third of the superior limiting sulcus and superior half of the anterior limiting sulcus. It narrows just above the UF at the level of the limen insulae, passes deep to the middle third of the inferior limiting sulcus, and continues backward within the superior and middle temporal gyri to reach the occipital lobe. After passing deep to the inferior limiting sulcus, the upper limit of the cortical distribution of the IFOF at the parieto-occipital cortex is located below a line connecting the midpoint of the limen insulae and the upper end of the parieto-occipital sulcus. This line is also positioned at the posterior edge of the claustrocortical fibers (Figures 2G, 2J, and 2K). The IFOF forms the main part of the ventral semantic pathway.[34] Although the IFOF could not be identified in the macaque monkey, we think that the IFOF in humans is comparable to the extreme capsule in the macaque. It has been noted that the IFOF connects the inferomedial occipital lobe and possibly the medial parietal lobe (precuneus) to the inferior frontal gyrus, the mid part of the middle frontal gyrus (dorsolateral prefrontal cortex), and the frontal pole, by passing through the superior and middle temporal gyri and temporal stem.[32] In our observations, the IFOF also projected to the posterior part of the parietal lobe. The IFOF is thought to play an important role in semantic processing, visual recognition, integration of the multimodal sensory input and motor planning, reading, and writing, as well as the comprehension and production of meaningful speech.[6,34,42,43] It has been noted that intraoperative electrostimulation of the entire IFOF produces semantic paraphasia (error with meaning of target word).[6,44] The IFOF has also been suggested as the medial limit of a left temporal lobectomy that will avoid postoperative language deficit.[6] The IFOF covers the optic radiation fibers as they pass deep to the superior and middle temporal gyri and occipital lobe and lateral to the temporal horn, atrium, and occipital horn of the lateral ventricle. Avoiding entering the depth of the IFOF during surgery aids in preventing injury to the optic radiations.

The UF, a frontotemporal association fiber pathway, connects the temporal pole to the lateral orbitofrontal area through its dorsolateral branch and the medial orbitofrontal and septal areas through its ventromedial branch (Figures 2J-2M).[45]

The UF courses just anterior to the anterior perforated substance and covers the inferior and medial sides of the nucleus accumbens to reach the area below the genu of the corpus callosum. In the subgenual area, the UF, which is considered to be a part of the ventral limbic pathway, comes together with the fibers of the cingulum, considered to be the dorsal limbic pathway.[33] Disconnection may result in behavioral disturbance.[33,45] The connection of the nucleus accumbens with the orbitofrontal area is provided by the ventromedial branch of the UF. The UF passes deep to the inferior half of the anterior limiting sulcus and most anterior part of the inferior limiting sulcus, forming a hook shape.

Medial to the external capsule is the lentiform nucleus formed by the putamen laterally and globus pallidus medially (Figures 2H and 2I). The lentiform nucleus is joined to the caudate nucleus by scattered bundles of gray matter that cross the anterior limb of the internal capsule, also referred to as the transcapsular bridges of gray matter (pontes grisei caudatolenticulares), to the basal forebrain by the extension called the fundus of the putamen (anteroventral part of the putamen), and to the amygdala by an inferior extension of the lentiform nucleus referred to as the peduncle of the lentiform nucleus.[37] Both the fundus and peduncle of the lentiform nucleus are collections of gray matter that cross the area between the lentiform nucleus and the adjoining nuclei (Figures 2P and 3D). Removing the putamen exposes the globus pallidus and anterior commissure. The globus pallidus sits just behind the anterior commissure and is involved in regulation of voluntary movements.[46] The term globus pallidus means “pale globe,” and in our examinations, its color was lighter than that of the putamen in all specimens (Figures 2I, 2N, and 2Q). The globus pallidus has an external part, located laterally, and an internal part, located medially. The external (lateral) part extends medially to the genu of the internal capsule, but the internal (medial) part faces only the posterior limb of the internal capsule (Figure 3F). The globus pallidus has primarily inhibitory control over movement. Damage to the globus pallidus may cause involuntary tremor, which is why pallidotomy is used to treat some movement disorders.[46]

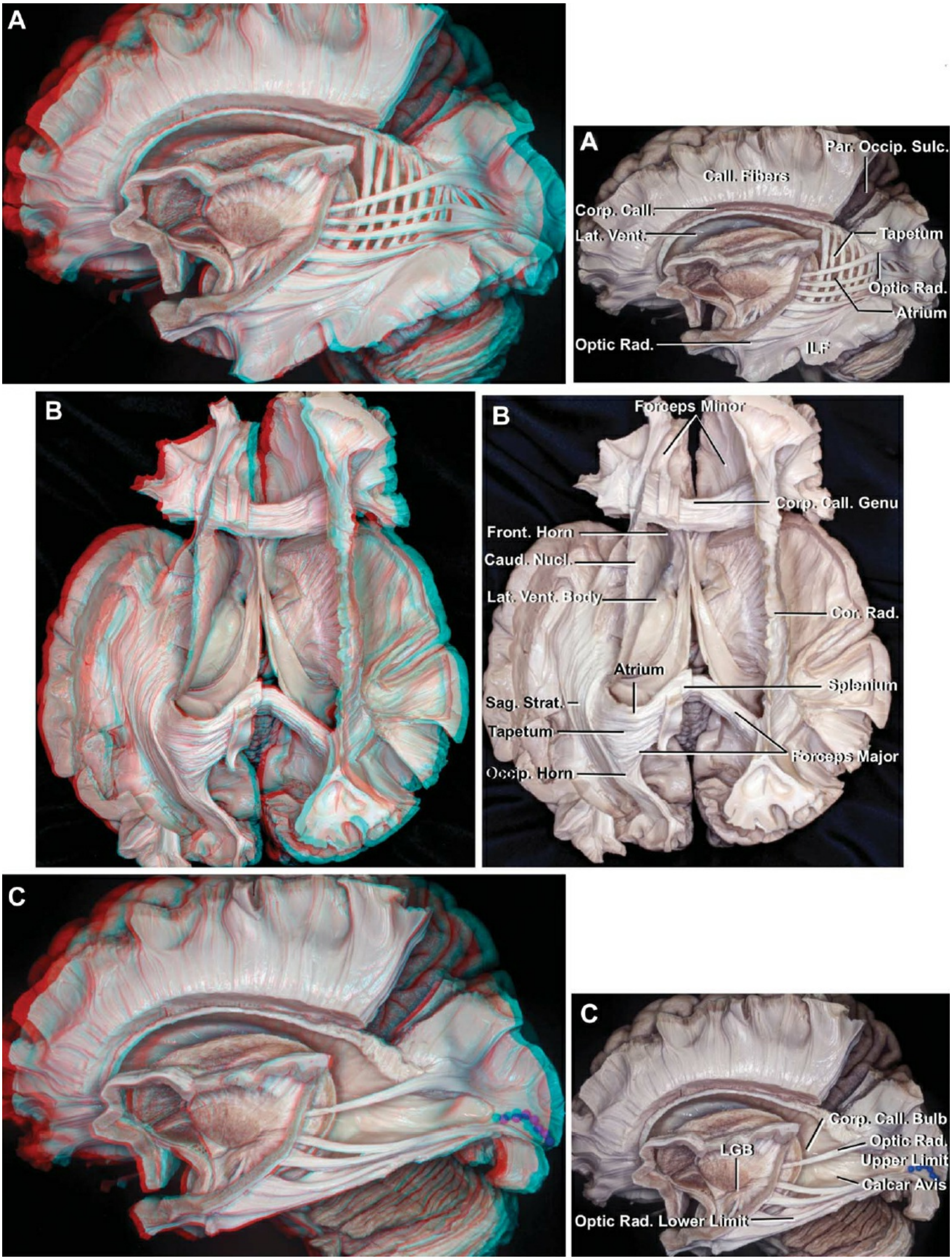


Figure 3 (A–C). Step-by-step continuation of the dissection in Figure 2. A, the ependyma in the lateral wall of the body and frontal horn of the lateral ventricle and intermittent bands of tapetal and optic radiation fibers have been removed. The optic radiations are separated from the temporal and occipital horns and the atrium of the lateral ventricle by the

tapetum. Tapetal fibers course in a vertical orientation while optic radiation fibers have a more horizontal orientation. B, superior view. The frontoparietal (corona radiata) and occipital (sagittal stratum) projections have been exposed. The atrium and occipital horn of the lateral ventricle are bordered laterally by the sagittal stratum and tapetal fibers and medially by the forceps major. The upper edge of the lateral wall of the frontal horn and body of the lateral ventricle are bordered by corona radiata fibers. C, the tapetal fibers have been removed to expose the bulb of the corpus callosum overlying the fibers of the forceps major, and the calcar avis overlying the deep end of the calcarine sulcus in the medial wall of the atrium of the lateral ventricle. After arising in the lateral geniculate body, the optic radiation fibers pass between the inferior limiting sulcus and tail of the caudate nucleus. AIP, anterior insular point; Amyg., amygdala; Ant., anterior; Call., callosal, callosum; Caps., capsule; Caud., caudate; Cing., cingulate; Claust., claustrum; Comm., commissure; Cor., corona; Corp., corpus; Front., frontal; Glob., globus; Gyr., gyrus; Hippo., hippocampus; ILF, inferior longitudinal fasciculus; Inf., inferior; Innom., innominata; Int., interna, internal; Lat., lateral; Lent., lenticular; LGB, lateral geniculate body; Lim., limiting; Med., medullaris; Nucl., nucleus; Occip., occipital; Pall., pallidus; Par., parietal, parieto; Ped., peduncle; PIP, posterior insular point; Rad., radiata, radiations; Sag., sagittal; Sept., septal; SLF, superior longitudinal fasciculus; Str., stria; Strat., stratum; Subst., substantia; Sulc., sulcus; Sup., superior; Term., terminalis; Thal., thalami; Vent., ventral, ventricle. (Images courtesy of AL Rhoton, Jr.)

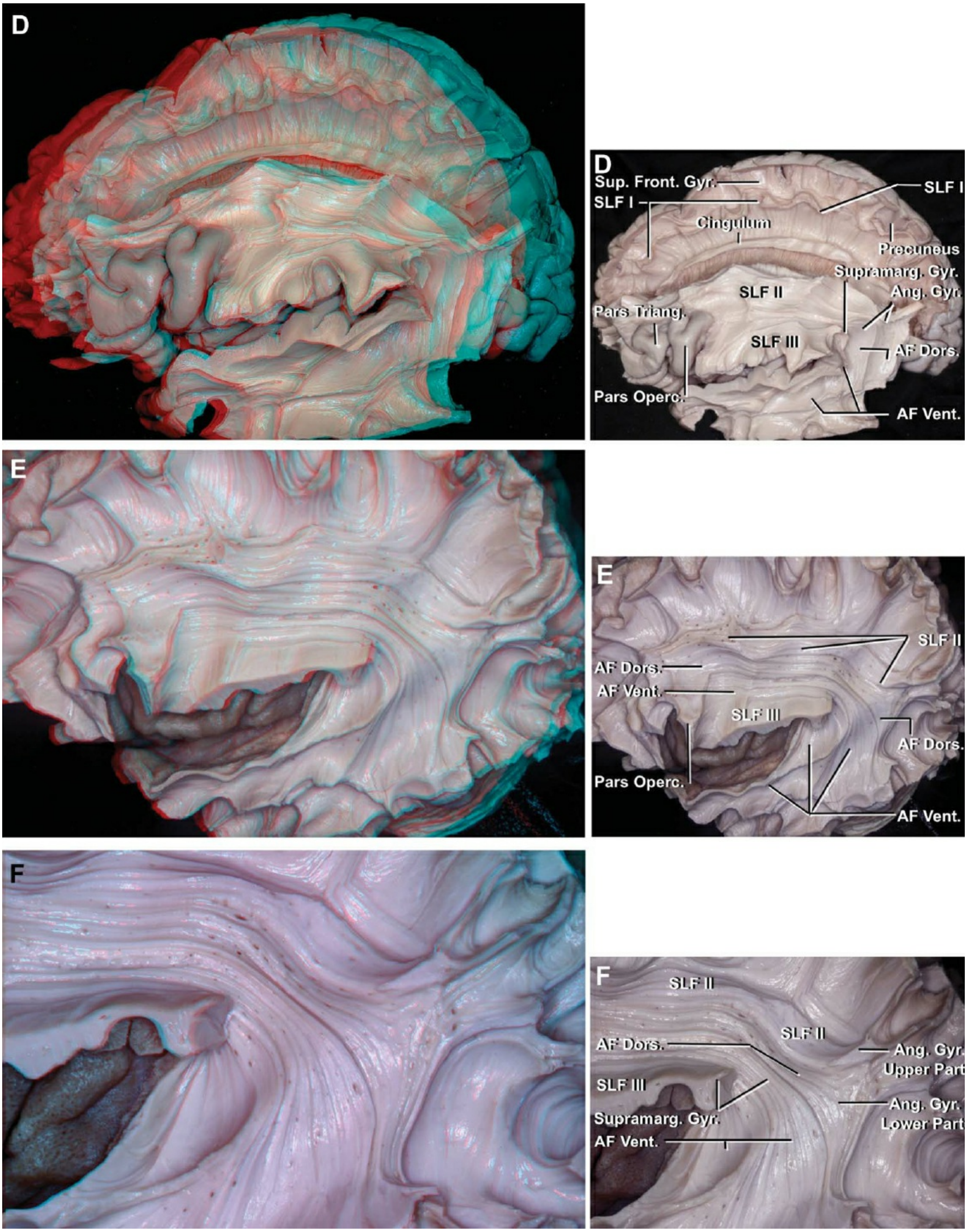


Figure 3 (D–F). D, the tail of the caudate nucleus crosses deep to the inferior limiting sulcus and blends into the amygdala. The peduncle of the lentiform nucleus intermingles with the amygdala without a clear demarcation between the 2 nuclei. The substantia innominata is located beneath and in front of the posterior crus of the anterior commissure and lateral to the anterior crus. E, the anterior insular point is positioned lateral to the frontal horn of the lateral ventricle. The posterior insular

point is positioned lateral to the tail of the caudate nucleus and the junction of the body and atrium of the lateral ventricle. The head of the caudate nucleus is positioned deep to and inside the borders of the insular area. The anterior insular point is positioned above the head of the caudate nucleus. The body of the caudate nucleus extends above the level of the superior limiting sulcus and passes deep to the posterior insular point. The tail of the caudate nucleus begins deep to the posterior insular point and passes deep to and below the posterior part of the inferior limiting sulcus. F, removal of the globus pallidus externus (lateral segment) exposes the globus pallidus internus (medial segment). AIP, anterior insular point; Amyg., amygdala; Ant., anterior; Call., callosal, callosum; Caps., capsule; Caud., caudate; Cing., cingulate; Claust., claustrum; Comm., commissure; Cor., corona; Corp., corpus; Front., frontal; Glob., globus; Gyr., gyrus; Hippo., hippocampus; ILF, inferior longitudinal fasciculus; Inf., inferior; Innom., innominata; Int., interna, internal; Lat., lateral; Lent., lenticular; LGB, lateral geniculate body; Lim., limiting; Med., medullaris; Nucl., nucleus; Occip., occipital; Pall., pallidus; Par., parietal, parieto; Ped., peduncle; PIP, posterior insular point; Rad., radiata, radiations; Sag., sagittal; Sept., septal; SLF, superior longitudinal fasciculus; Str., stria; Strat., stratum; Subst., substantia; Sulc., sulcus; Sup., superior; Term., terminalis; Thal., thalami; Vent., ventral, ventricle. (Images courtesy of AL Rhoton, Jr.)

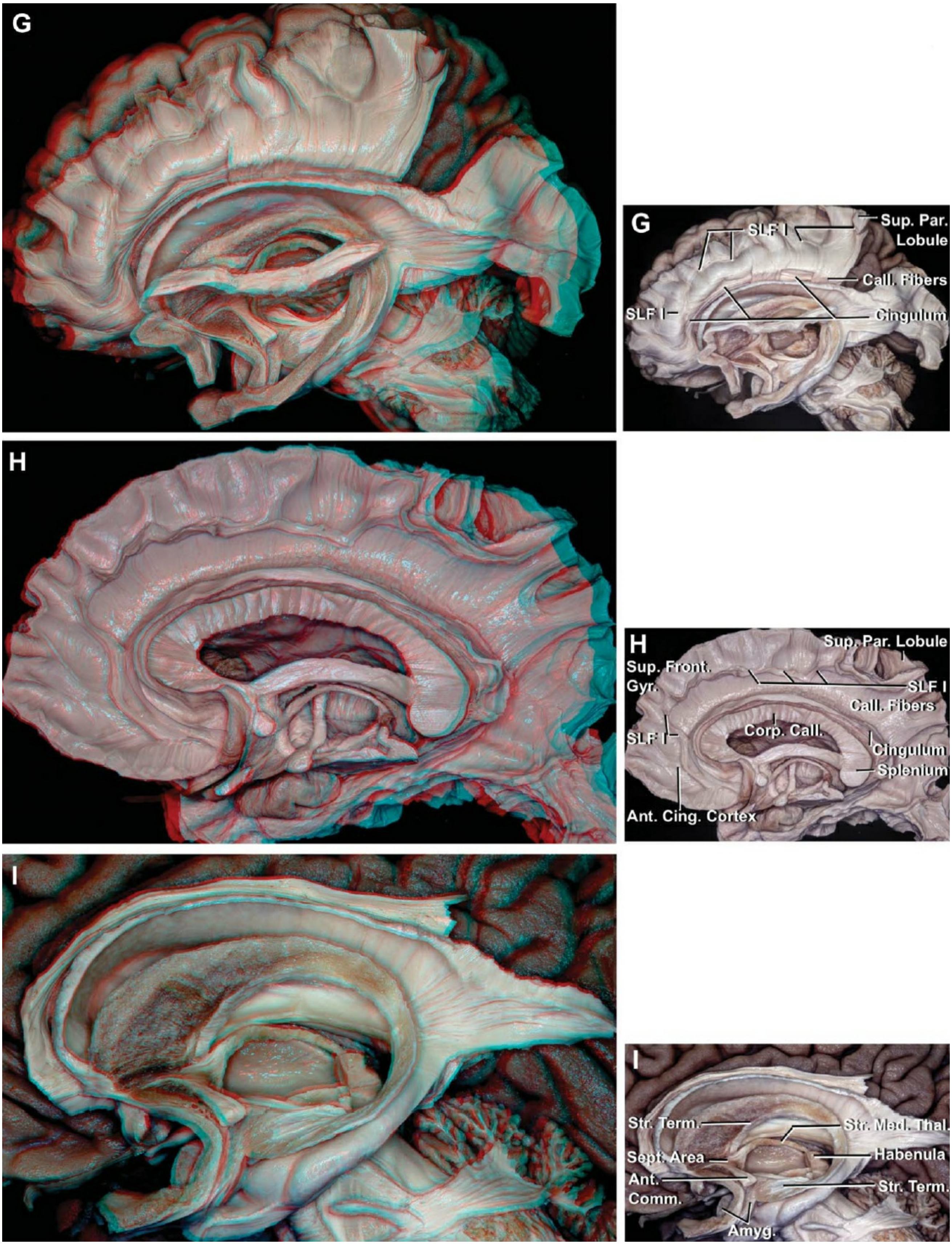


Figure 3 (G–I). G, lateral view of the SLF I located just medial to the callosal fibers and above the cingulum. H, medial view of the SLF I. It sits within the upper bank of the cingulate sulcus and courses medial to the callosal fibers and above the cingulum. I, lateral view. The limiting sulci and thalamus were removed to expose the striae terminalis and striae medullaris thalami. The stria terminalis arises from the bed nucleus of the

stria terminalis, located adjacent to the anterior commissure in the septal area, and wraps around the thalamus to blend into the amygdala. The stria medullaris thalami connects the septal area and habenula and separates the dorsal from the medial thalamic surface. AIP, anterior insular point; Amyg., amygdala; Ant., anterior; Call., callosal, callosum; Caps., capsule; Caud., caudate; Cing., cingulate; Claust., claustrum; Comm., commissure; Cor., corona; Corp., corpus; Front., frontal; Glob., globus; Gyr., gyrus; Hippo., hippocampus; ILF, inferior longitudinal fasciculus; Inf., inferior; Innom., innominata; Int., interna, internal; Lat., lateral; Lent., lenticular; LGB, lateral geniculate body; Lim., limiting; Med., medullaris; Nucl., nucleus; Occip., occipital; Pall., pallidus; Par., parietal, parieto; Ped., peduncle; PIP, posterior insular point; Rad., radiata, radiations; Sag., sagittal; Sept., septal; SLF, superior longitudinal fasciculus; Str., stria; Strat., stratum; Subst., substantia; Sulc., sulcus; Sup., superior; Term., terminalis; Thal., thalami; Vent., ventral, ventricle. (Images courtesy of AL Rhoton, Jr.)

Commissural and Projection Fibers

The anterior commissure crosses the midline at the base of the putamen to connect the orbitofrontal, occipital, and temporal lobes, and especially the amygdala (Figures 2N-2R).[33] The anterior commissure, located immediately in front of the columns of the fornix, resembles bicycle handlebars. It forms part of the anterior wall of the third ventricle (Figures 2M and 2P-2R). The anterior commissure has an anterior crus that extends forward toward the olfactory nucleus and reaches the medial orbitofrontal area and a posterior crus that extends laterally and divides into temporal and occipital extensions.[47] The anterior crus forms the border between the nucleus accumbens medially and substantia innominata laterally (Figures 2P and 2Q).[33,45] It extends forward just below the ventral surface of the anterior limb of the internal capsule. The posterior crus of the anterior commissure runs laterally within Gratiolet's canal and undergoes torsion so that its superior fibers run to the temporal lobe and its inferior fibers reach the occipital lobe (Figure 2O).[48] The posterior crus passes deep to the anterior two-thirds of the inferior limiting sulcus and medial to the IFOF. The temporal extension of the posterior crus courses downward to the temporal pole and amygdala just behind the UF, and the occipital extension passes deep to the superior and middle temporal gyri to reach the occipital lobe. The anterior commissure is an important interhemispheric connection in epilepsy surgery. Its temporal extension has been suggested as a pathway for rapid propagation of seizure activity between the medial temporal lobes that should be divided in hemispherotomy or functional hemispherectomy.[33] Its occipital extension has also been shown to be capable of conveying interhemispheric visual information in patients born without a corpus callosum.[33] Visual information is processed in part by the anterior commissure's occipital extension and splenium of the corpus callosum.[33] Anterior to and beneath the posterior crus of the anterior commissure is the substantia innominata, formed by the nucleus basalis of Meynert, which provides cholinergic input for the cortex.[33,49,50] The lenticulostriate arteries supplying the central core structures penetrate the anterior perforated substance and pass adjacent the anterior and posterior edges of the anterior commissure.

The basal forebrain sits in front of and below the level of the posterior crus of the anterior commissure, which includes, among other structures, the substantia innominata, nuclei basalis and accumbens, diagonal band of Broca, medial septal nuclei, and extended amygdala, the continuation of the amygdaloid complex to the bed nucleus of the stria terminalis (Figure 2P).[45,47] The substantia innominata, containing the basal nucleus, is located anterior to the posterior crus and lateral to the anterior crus of the anterior commissure and the anterior limb of the internal capsule and above the anterior perforated substance. The gray matter forming the fundus (anteroventral part) of the putamen blends into the substantia innominata, located above the anterior perforated substance without a clear border between the 2 areas. The nucleus accumbens is situated medial to the anterior crus of the anterior commissure and anterior limb of the internal capsule and below the level of the anterior commissure. The septal area is located adjacent the midline in front of the anterior commissure. Neurophysiologically, there is no clear demarcation between the substantia innominata and nucleus accumbens or between the septal nuclei and head of the caudate nucleus.[33,47,49,50]

The internal capsule, composed of projection fibers, is positioned just medial to the lentiform nucleus (Figures 2I and 2Q). The anterolateral and posterolateral edges of the internal capsule in axial sections join at a nearly right angle that faces the anteromedial and posteromedial margins of the lentiform nucleus, respectively. The internal capsule has 3 parts: the anterior limb, posterior limb, and genu. The anterior limb of the internal capsule passes between the putamen and the head of the caudate nucleus.[37] The genu of the internal capsule, at the junction of its anterior and posterior limbs, is located just behind the anterior commissure in the same coronal plane as the foramen of Monro and posterior short insular gyrus.[37] The internal capsule undergoes torsion in the same direction as the anterior commissure, placing the lower part of the posterior limb further lateral than the anterior limb (Figures 2O and 2Q).[17,33]

The genu of the internal capsule includes the corticobulbar fibers, which connect the lower third of the precentral gyrus to the relevant cranial nuclei in the brainstem, and the fibers of the anterior and superior frontal thalamic radiations.[33,51] The anterior limb of the internal capsule contains fibers of the anterior and superior frontal thalamic radiations and frontopontine tract (Figures 2T-2V).[33,51,52] The most laterally located fibers in the anterior limb of the internal capsule arise from the frontal operculum. The fibers in the middle part of the anterior limb of the internal capsule arise from the prefrontal cortex, including the frontal pole, run horizontally in the internal capsule, and pass backward through the anterior limb and genu of the internal capsule to reach the thalamus. The fibers emanating from the medial frontal area and anterior portion of the cingulate cortex are positioned most medially in the anterior limb.[17,53,54]

The posterior limb of the internal capsule is located between the lentiform nucleus and thalamus. The posterior limb contains the corticospinal, corticopontine, corticotegmental, and parietal thalamic radiations (postcentral or superior thalamic radiations in the literature).[51,52] It also contains some frontopontine fibers from Brodmann areas 4 and 6 and the frontorubral fibers. The corticospinal fibers arise from adjacent the central sulcus and pass through the anterior part of the posterior limb of the internal capsule.

The anterior, superior, and posterior limits of the internal capsule are located between the rostromedial margin of the putamen and superolateral edge of the caudate nucleus. The external capsule joins the internal capsule at the upper edge of the lentiform nucleus to form the corona radiata (Figures 2I and 2N).[17] The medial edge of the genu and posterior limb of the internal capsule face the reticular nucleus of the thalamus, and the medial edge of the anterior limb faces the head of the caudate nucleus. The inferior limits of the parts of the internal capsule are the level of the anterior commissure for the anterior limb, the hypothalamus for the genu, and the lateral geniculate body for the posterior limb (Figure 2Q).[17]

The frontoparietal projection fibers located above the upper edge of the putamen are called the corona radiata, although the precise location and fiber type of the corona radiata are not clearly established in the literature.[51] They include the internal and dorsal external capsule fibers and correspond to pre- and supralentiform fibers (Figures 2T, 2U, and 3B). The corona radiata contains the corticospinal, corticopontine, and thalamocortical fibers in the internal capsule medially and the claustrocortical fibers in the external capsule laterally. The frontoparietal projection fibers pass through the genu and anterior and posterior limbs of the internal capsule. The corticothalamic or thalamocortical fibers separate from the corona radiata and internal capsule to enter the thalamus and form the thalamic radiations.[47,49]

A line connecting the upper end of the parieto-occipital sulcus and the midpoint of the limen insulae separates the corona radiata above from the sagittal stratum, composed of occipital and temporal projection fibers, below (Figure 2S). This line also corresponds to the posterior border of the claustrocortical (dorsal external capsule) and parietal projection fibers, and upper border of the IFOF (ventral external capsule) (Figures 2J and 2S). The occipital projection fibers are composed of the occipitopontine and occipitothalamic fibers and are bordered laterally by association fibers including the IFOF, MdLF, and ILF (Figures 2S-2U and 3B). The occipital thalamic radiations are formed by the optic radiations that travel from the lateral geniculate body and the pulvinar to the calcarine cortex (Figures 3A-3C).[47]

The thalamic radiations are named according to their associated cortical areas such as the superior and anterior frontal, parietal, and occipital thalamic radiations rather than according to their connection in the thalamus, such as anterior, posterior, superior (central), and inferior thalamic radiations (Figures 2T-2V and 3A-3D). Naming the thalamic fibers based on their thalamic rather than their cortical connection results in there being 2 inferior thalamic radiations: the fibers originating from the orbitofrontal cortex or those from the amygdala (branch of the ansa peduncularis).[17,55] The corticothalamic fibers are positioned medial to the corticospinal and corticopontine fibers in the internal capsule.[47] The anterior frontal thalamic radiation, which courses obliquely downward and backward, passes through the anterior limb of the internal capsule and genu to reach the dorsomedial thalamus.[17] The superior frontal thalamic radiation from above courses first vertically and then in a posterior direction passes medial to the anterior frontal thalamic radiation and through the genu and anterior and posterior limbs of the internal capsule to reach the thalamus. The parietal thalamic radiation passes through the posterior limb of the internal capsule to reach the thalamus. The occipital thalamic radiation (optic radiations) is arranged in 3 bands: anterior, central, and posterior. The anterior band of optic radiations, which courses in an anterolateral direction, usually reaches as far anteriorly as the tip of the temporal horn of the lateral ventricle just behind the temporal extension of the anterior commissure where the fibers turn backward in a loop (Meyer's loop). This band covers the roof and lateral wall of the temporal horn and inferior surface of the atrium of the lateral ventricle, reaching the lower lip of the calcarine sulcus. The central band of optic radiations courses downward from the lateral geniculate body and pulvinar, and then turns back to reach the calcarine cortex. The posterior band of optic radiations, after arising from the lateral geniculate body and pulvinar, runs directly backward to reach the upper lip of the calcarine sulcus.

Frontal Lobe Dissections

The cortical boundaries for a frontal lobectomy are 7 to 8 cm posterior to the frontal pole, avoiding the precentral and inferior frontal gyri (Figure 4).[56] The basic eloquent cortical and subcortical boundaries for a safe frontal lobectomy are the precentral gyrus and its underlying fibers posteriorly, the inferior frontal gyrus and arcuate fasciculus inferiorly, and the head of the caudate nucleus and frontal horn of the lateral ventricle medially.[57]

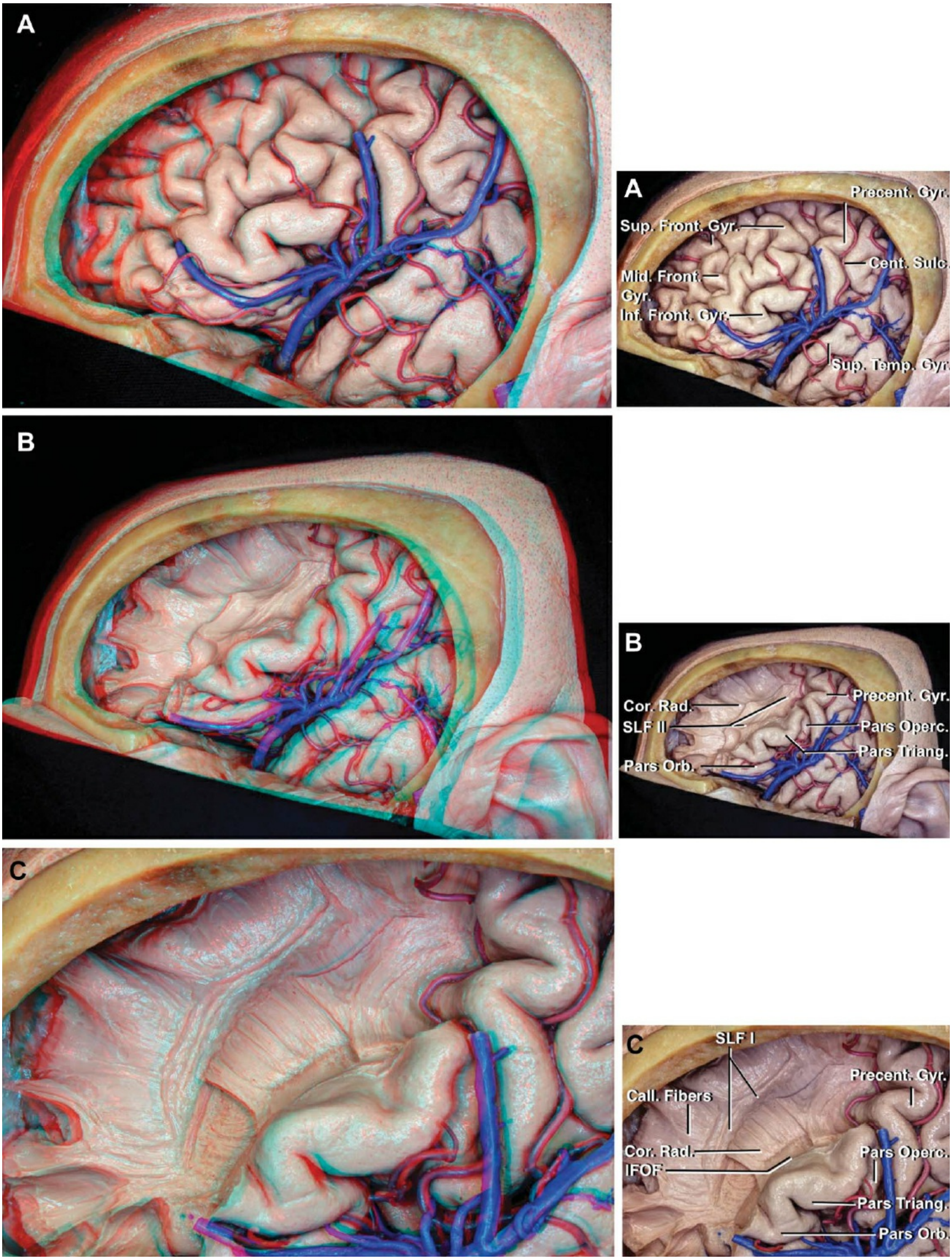


Figure 4 (A–C). A, a left frontotemporal craniotomy has been performed. The superficial sylvian veins and frontal and temporal lobes have been exposed. B, the fiber tracts deep to the superior and middle frontal gyri have been exposed while preserving the precentral and inferior frontal gyri. The cortex and short association fibers were removed to expose the

SLF II, which courses deep to the middle frontal gyri. The corona radiata has been exposed. C, proceeding medially, the removal of the SLF II exposes the IFOF deep to the mid part of the middle frontal gyrus and the corona radiata. Removal of the corona radiata fibers at the level of the superior frontal gyrus exposes the callosal fibers. Some of the callosal fibers have been removed to expose the SLF I. AF, arcuate fasciculus; AIP, anterior insular point; Ant., anterior; Call., callosal, callosum; Caps., capsule; Caud., caudate; Cent., central; Cor., corona; Corp., corpus; Dors., dorsal; Front., frontal; Glob., globus; Gyr., gyrus; IFOF, inferior fronto-occipital fasciculus; Inf., inferior; Ins., insular; Int., internal; Lat., lateral; Lim., limiting; Mid., middle; Operc., opercularis; Orb., orbitalis; Pall., pallidus; Precent., precentral; Rad., radiata; SLF, superior longitudinal fasciculus; Sulc., sulcus; Sup., superior; Temp., temporal; Triang., triangularis; UF, uncinate fasciculus; Vent., ventral, ventricle. (Images courtesy of AL Rhoton, Jr.)

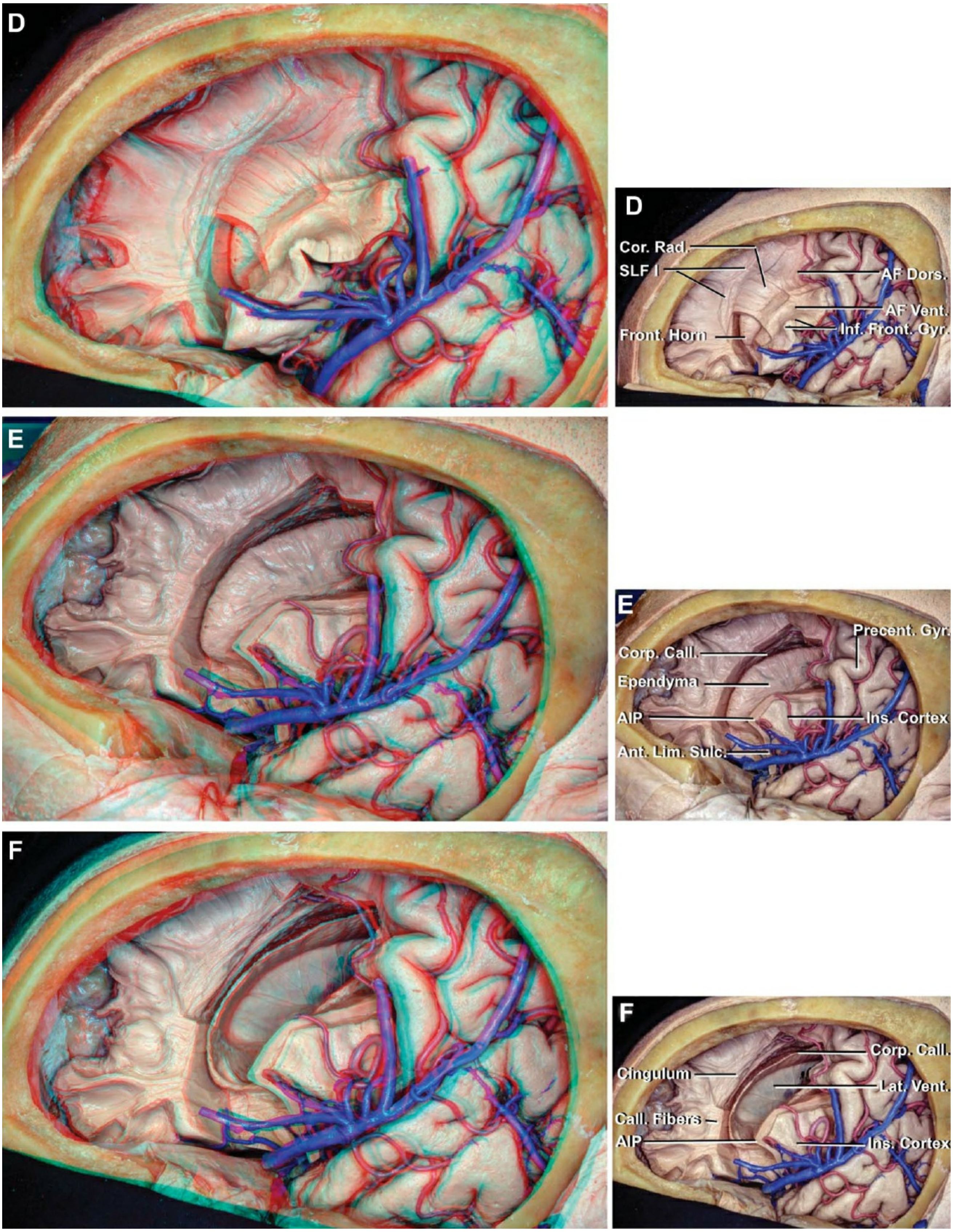


Figure 4 (D–F). D, extending the exposure deep to the middle and inferior frontal gyri exposes the frontal horn of the lateral ventricle and the AF ventral and dorsal segments. The corpus callosum and SLF I are exposed above the lateral ventricle. E, the inferior frontal gyrus has been removed to expose the insular cortex. The corpus callosum has been exposed above the ependyma of the lateral ventricle. F, the lateral ventricle,

corpus callosum, and insular surface have been exposed. The anterior insular point is positioned lateral to the frontal horn of the lateral ventricle. Further removal of callosal fibers exposes the cingulum. AF, arcuate fasciculus; AIP, anterior insular point; Ant., anterior; Call., callosal, callosum; Caps., capsule; Caud., caudate; Cent., central; Cor., corona; Corp., corpus; Dors., dorsal; Front., frontal; Glob., globus; Gyr., gyrus; IFOF, inferior fronto-occipital fasciculus; Inf., inferior; Ins., insular; Int., internal; Lat., lateral; Lim., limiting; Mid., middle; Operc., opercularis; Orb., orbitalis; Pall., pallidus; Precent., precentral; Rad., radiata; SLF, superior longitudinal fasciculus; Sulc., sulcus; Sup., superior; Temp., temporal; Triang., triangularis; UF, uncinate fasciculus; Vent., ventral, ventricle. (Images courtesy of AL Rhoton, Jr.)

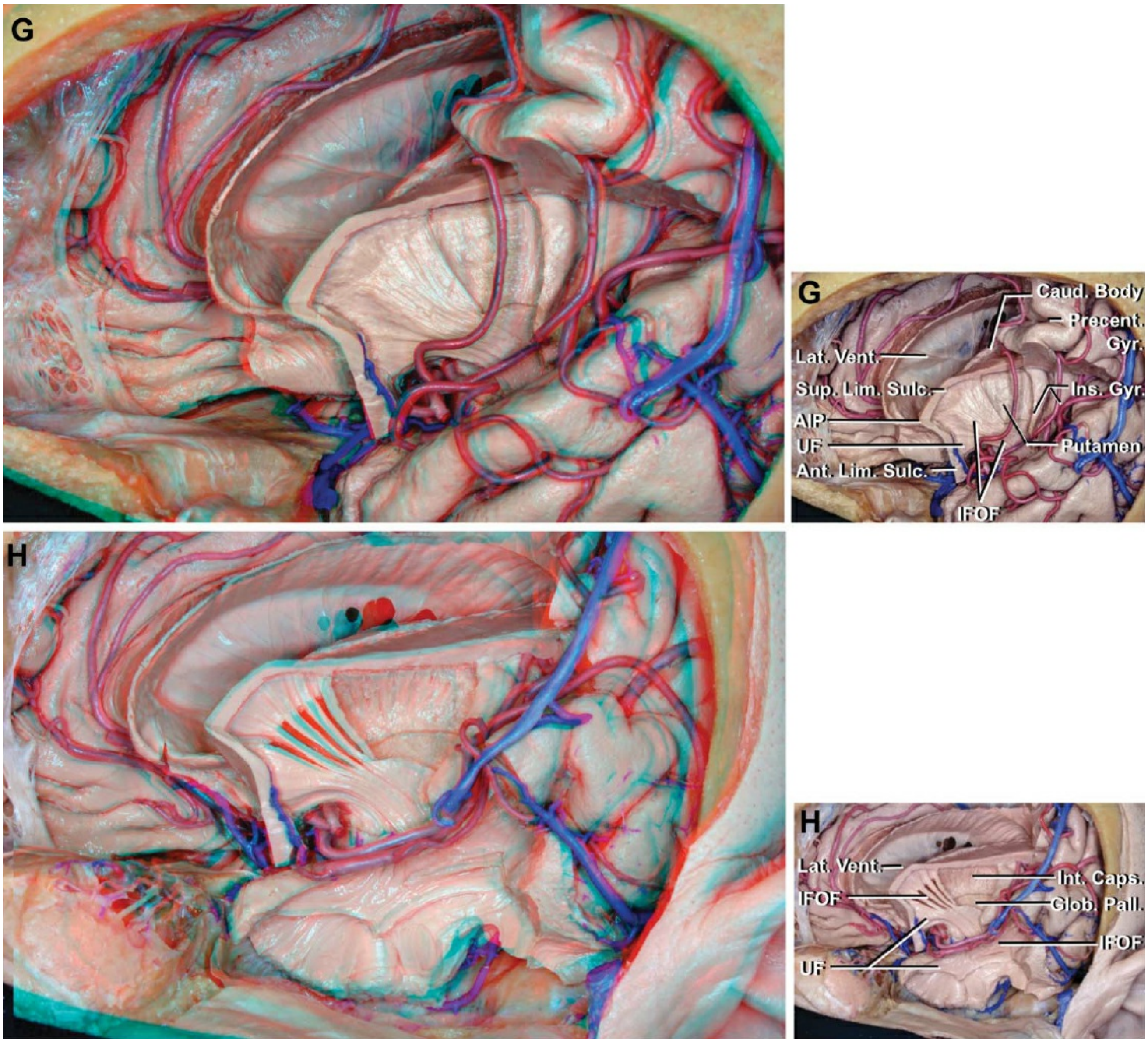


Figure 4 (G–H). G, the insular cortex has been removed. The IFOF passes deep to the anterior third of the superior limiting sulcus and superior half

of the anterior limiting sulcus, and the UF passes deep to the inferior half of the anterior limiting sulcus. H, the putamen has been removed deep to the preserved bands of the IFOF to expose the internal capsule and globus pallidus. The UF in the temporal lobe has been exposed. AF, arcuate fasciculus; AIP, anterior insular point; Ant., anterior; Call., callosal, callosum; Caps., capsule; Caud., caudate; Cent., central; Cor., corona; Corp., corpus; Dors., dorsal; Front., frontal; Glob., globus; Gyr., gyrus; IFOF, inferior fronto-occipital fasciculus; Inf., inferior; Ins., insular; Int., internal; Lat., lateral; Lim., limiting; Mid., middle; Operc., opercularis; Orb., orbitalis; Pall., pallidus; Precent., precentral; Rad., radiata; SLF, superior longitudinal fasciculus; Sulc., sulcus; Sup., superior; Temp., temporal; Triang., triangularis; UF, uncinate fasciculus; Vent., ventral, ventricle. (Images courtesy of AL Rhoton, Jr.)

The frontal lobe was dissected while initially preserving the precentral and inferior frontal gyri. The cortex and short association fibers were removed at the level of the middle frontal gyrus to expose the SLF II 2 cm deep to the cortical surface. Proceeding medially, removal of the SLF II exposed the AF dorsal segment in the posterior part of the middle frontal gyrus and the IFOF in the mid part of the middle frontal gyrus 3 cm deep to the surface and the corona radiata fibers, including the claustrocortical and frontopontine fibers and frontal thalamic radiations at a depth of more than 3 cm. The superior frontal thalamic radiations ran in an oblique orientation, and the anterior frontal thalamic radiations traveled horizontally and more superficial than the superior frontal thalamic radiations. At the level of the superior frontal gyrus, the corona radiata fibers were exposed 1.5 cm below the cortical surface. Removal of the corona radiata exposed the callosal fibers 2 cm deep to the surface and SLF I 2.2 cm deep to the surface. Removing the inferior frontal gyrus at a later stage of dissection exposed the insular cortex and the IFOF 0.6 cm deep to the anterior insular cortex. The IFOF passed deep to the anterior third of the superior limiting sulcus and superior half of the anterior limiting sulcus, whereas the uncinate fasciculus passed deep to the inferior half of the anterior limiting sulcus. Further dissection in the depth of the middle and inferior frontal gyri exposed the frontal horn and body of the lateral ventricle 4 cm from the surface, and the AF segments in the inferior frontal gyrus. The corpus callosum courses in the roof of the lateral ventricle. The frontal horn and body of the lateral ventricle are positioned medial to the inferior frontal gyrus, but, if enlarged, they extend upward to the level of the middle frontal gyrus.

Frontal Lobe Anatomy and Function

Topographically, the middle frontal gyrus can be divided into an anterior part, which includes the frontopolar cortex (Brodmann area [BA] 10), a middle part including the dorsolateral prefrontal cortex (BAs 9 and 46), and a posterior part that includes the premotor (BAs 6 and 8) and motor (BA 4) cortices.[1] The inferior frontal gyrus includes the ventrolateral prefrontal cortex (BAs 44, 45, and 47). Damage to the motor cortex (BA 4) and underlying corticospinal tract produces contralateral hemiplegia or paresis. Anterosuperior to the precentral gyrus are the frontal eye fields, damage to which may cause gaze abnormalities.[58,59] The mid part of the middle frontal gyrus, referred to as the dorsolateral prefrontal cortex (BAs 9 and 46), is involved in cognition. Damage to it and its underlying fiber pathways results in disorders characterized by memory deficits, increased inhibition, and impaired abstract thinking and goal-directed executive functions.[1,2,60-62] The dorsolateral prefrontal cortex has also been noted to be a semantic center. Electrostimulation of this cortical area and the underlying IFOF produces semantic paraphasia.[4,60] The dorsolateral prefrontal cortex is connected in order laterally to medially to the rest of the frontal cortex by short association fibers, the inferior parietal lobe by the SLF II, the occipital and temporal lobes by the IFOF, the basal ganglia and thalamus by the frontal thalamic radiations, the contralateral prefrontal cortex by the forceps minor, and the hippocampus (or limbic system) by the cingulum.[1,14,63]

Damage to the frontal operculum, which contains the frontal segments of the SLF III and AF, may produce anarthria/dysarthria and aphasia/dysphasia, respectively.[20,21] It has also been reported that unilateral electrical stimulation or surgical resection of the underlying fiber pathway up to the head of the caudate nucleus at the level of the dorsal premotor cortex (BA 6) may cause bilateral motor deficit (arrest of movement without any loss of tonus), whereas stimulation or damage to the fiber tract (pyramidal tract) underlying the motor cortex may cause contralateral motor deficit.[64,65] The ventral premotor cortex (inferior BA 6) has poor plastic potential, and damage to the cortex and underlying fiber tracts (SLF III) may cause irreversible speech disorders (anarthria/dysarthria).[20,66]

The inferior frontal gyrus (ventrolateral prefrontal cortex) is formed by the pars orbitalis, opercularis, and triangularis and includes Broca's area located on the pars opercularis and a small part of the pars triangularis. Stimulation of the left inferior frontal cortex induces paraphasia (more posterior stimulation induces phonemic paraphasia and more anterior stimulation induces semantic paraphasia), possibly including syntactic errors.[67,68] The fiber tracts underlying the inferior frontal gyrus, from superficial to deep, are the short U association fibers, SLF III, AF ventral and dorsal segments, IFOF, and corona radiata. The medial limits of the fiber tracts are the caudate nucleus and the frontal horn and body of the lateral ventricle.

Lesions in the medial frontal lobe, particularly in the anterior cingulate cortex, are characterized by apathy, loss of motivation, reduced goal-directed action, and lack of curiosity and interest.[69,70] More posterior lesions of the medial surface of the superior frontal lobe may also cause a reduction of spontaneous movement and mutism.[71] The medial prefrontal cortex connects to the medial surface of the other lobes by the cingulum, to the contralateral medial frontal cortex by the forceps minor, and to the precuneus (medial parietal lobe) by the SLF I.[1,13,14,19]

The orbitofrontal surface is divided into medial and lateral parts. The medial orbitofrontal cortex connects with the medial temporal structures, nucleus accumbens, and septal and olfactory areas by means of the ventromedial part of the UF, whereas the lateral orbitofrontal cortex connects with the temporal pole and dorsolateral prefrontal cortex by means of the dorsolateral part of the UF and the IFOF, respectively.

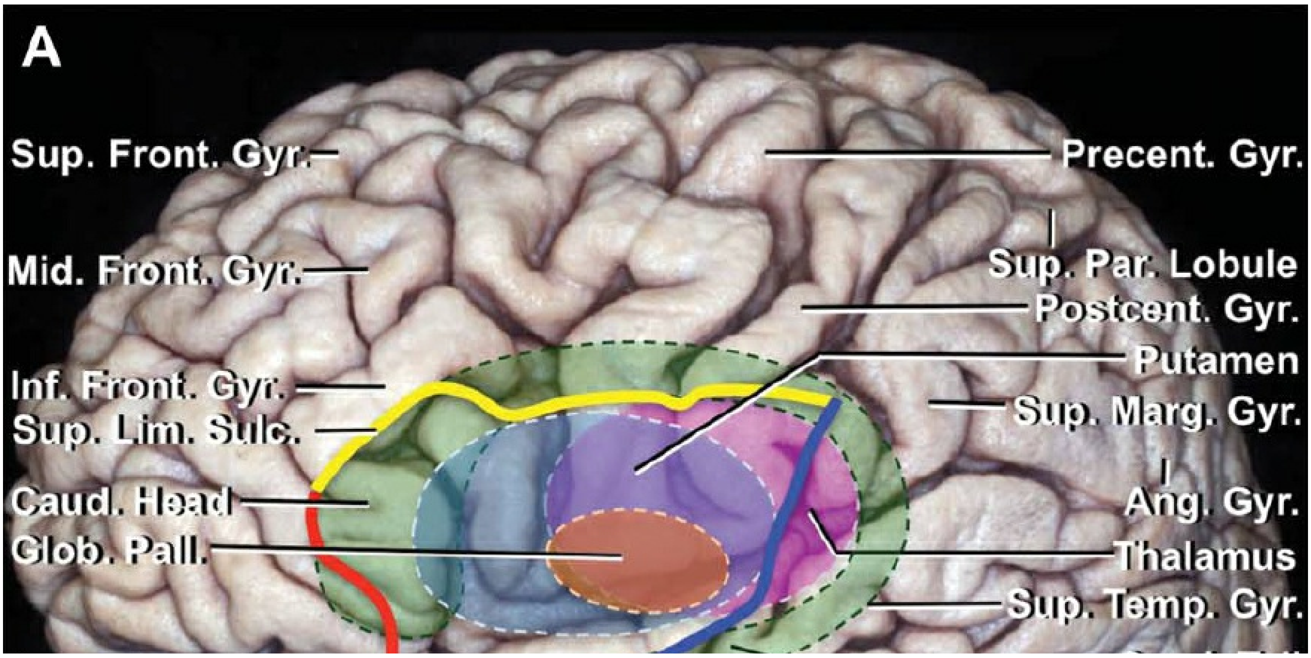
Connection to the contralateral orbitofrontal area is provided by the forceps minor and the anterior crus of the anterior commissure (Figures 2L, 2M, and 2P). The orbitofrontal cortex is related to behavioral processing. Effects of damage to this cortex and underlying fiber pathways differ significantly depending on location and in general include personality changes characterized by disinhibition, social inappropriateness, and sexual preoccupation.[1,72,73]

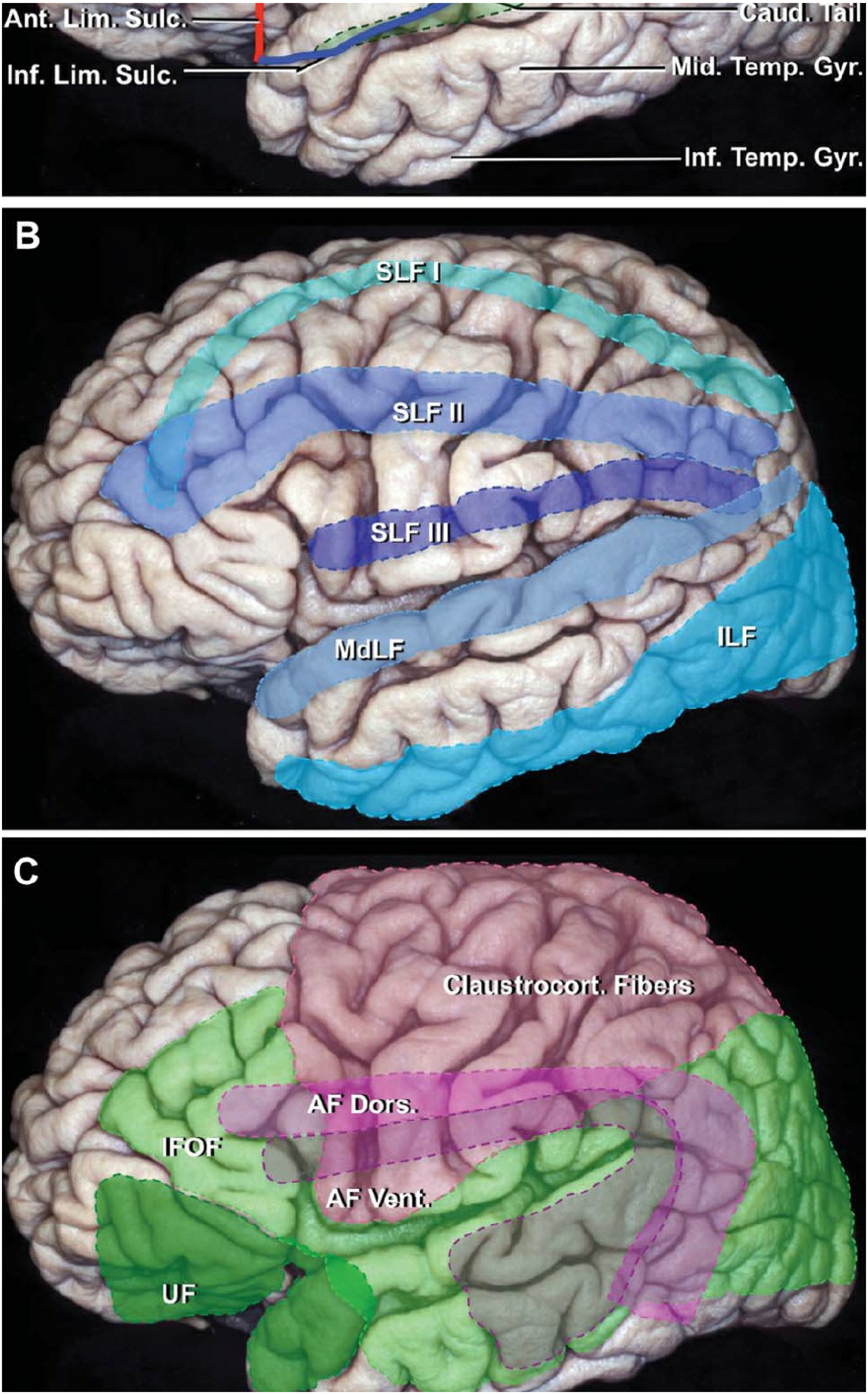
The conventional eloquent cortical areas in the frontal lobe are the inferior frontal gyrus (Broca's area) and precentral gyrus (motor cortex).[57] The premotor fibers, SLF, and IFOF underlying the inferior frontal gyrus have also been noted as eloquent subcortical fiber tracts.[57,74] The IFOF and SLF II underlying the middle frontal gyrus should be preserved to avoid postoperative deficits.

DISCUSSION

In previous publications, we emphasized the importance of developing a 3-D concept of the brain based on the relationships of superficial cranial landmarks to deep structures.[37] This concept has been enhanced in previous publications by 3-D photography of both microsurgical and endoscopic anatomy and approaches.[33,75] Relationships previously examined include the position of superficial landmarks such as the cranial sutures to superficial and deep cerebral structures and the relationship of superficial cerebral structures to deep and even midline structures to build a roadmap in the mind of the surgeon for navigating at different depths of the cerebrum.[37] There are many other examples, including the relationships of the fiber tracts to the safe entry zones in the brainstem.[75]

Some of the "first-time" fiber dissection findings displayed in this study include (1) the three subdivisions of the superior longitudinal fasciculus (Figures 1, 3G, and 3H); (2) the relationship between the 3 divisions of the SLF and dorsal and ventral segments of the arcuate fasciculus (Figure 1D); (3) the relationship between the middle longitudinal fasciculus and IFOF at the level of the posterior insular point (Figures 1H and 1I); (4) upward bending at 45° of the inferior longitudinal fasciculus at the level of the preoccipital notch (Figures 1H, 2G, and 2K); (5) the relationships of the basal ganglia and fiber tracts in the central core to the superior, anterior, and inferior limiting sulci of the insula (Figures 2 and 3); (6) the ventromedial and dorsolateral segments of the UF and the connections of the UF (ventral limbic pathway) and cingulum (dorsal limbic pathway) in the subgenual area (Figures 2L and 2M); (7) the relationship between the basal ganglia structures in the central core (Figures 2B, 2C, 2M, 2P, and 3D-3F); (8) rotation of the anterior commissure and distribution of its fibers (Figures 2N-2P); (9) the nuclear and fiber tract borders of each part of the internal capsule (Figure 2Q); (10) the borders between the corona radiata and sagittal stratum, between the claustrocortical fibers (dorsal external capsule) and IFOF (ventral external capsule), and between the parietal projection and occipital projection fibers and demonstrated in fiber dissection of the fibers forming the centrum semiovale (Figures 2G, 2J, 2S, and 2U); (11) fiber tracts composing the anterior limb of the internal capsule in order laterally to medially (Figures 2T-2V); (12) thalamic radiations based on the cortical connections of the thalamic fibers (Figures 2T-2W); (13) relationship of the optic radiations to the inferior limiting sulcus, atrium and temporal horn of the lateral ventricle, and adjacent fiber tracts (Figures 2T-2W and 3A-3D); (14) frontal lobe fiber tract anatomy in step-by-step dissections in the surgical view (Figure 4); and (15) topographic anatomy of the fiber tracts in relation to cortical gyri and their depth from the surface of the cortical gyri (Figures 5A-5E and 6A-6C and Tables 1 and 2).




Ant. Lim. Sulc.
Caud. Tail
Inf. Lim. Sulc.
Mid. Temp. Gyr.
Inf. Temp. Gyr.
B
SLF I
SLF II
SLF III
MdLF
ILF
C
Claustrocort. Fibers
AF Dors.
IFOF
AF Vent.
UF

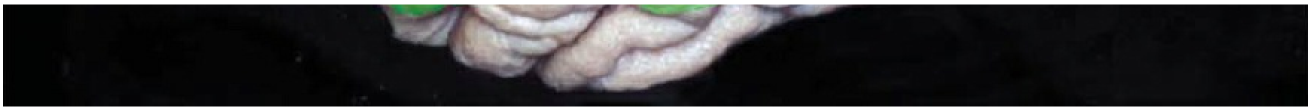


Figure 5 (A–C). A, the structures in the central core of the cerebrum have been superimposed on the cortical surface. The anterior (red), superior (yellow), and inferior (blue) limiting sulci outline the lateral surface of the central core formed by the insula. The anterior limiting sulcus is located deep to the anterior edge of the pars triangularis. The anterior part of the superior limiting sulcus is located medial to the inferior frontal gyrus, and the posterior part of the sulcus is located medial to the junction of the lower and middle third of the pre- and postcentral gyri and anterior part of the supramarginal gyrus. The inferior limiting sulcus is located deep to the superior temporal sulcus. The anterior part of the head of the caudate extends to the anterior limiting sulcus. The upper edge of the body extends slightly above the level of the superior limiting sulcus, and a segment of the tail extends backward and inferior to the level of the inferior limiting sulcus. The tail of the caudate nucleus, as it proceeds anteriorly, passes above the anterior part of the inferior limiting sulcus to blend into the amygdala. Other structures in the central core include the putamen, globus pallidus, and thalamus. B, long association pathways. The SLF I extends deep to the superior frontal gyrus and the superior parietal lobule. The SLF II passes deep to the middle frontal gyrus and midlevel of the pre- and postcentral gyri and deep to the upper part of the supramarginal and angular gyri. The SLF III passes deep to the inferior frontal gyrus, the lower part of the pre- and postcentral gyri, and the lower part of the supramarginal gyrus. The MdLF passes deep to or through the superior temporal and angular gyri and the ILF medial to the inferior temporal gyrus and dorsolateral occipital cortex. C, position of the UF, IFOF, claustrocortical fibers, and the dorsal and ventral segments of the AF in relation to the cortical surface. The UF passes medial to the temporal pole, anterior part of the superior and middle temporal gyri, and limen insulae and connects to the medial and lateral orbitofrontal areas. The IFOF passes deep to the mid part of the middle frontal gyrus and anterior part (pars orbitalis and triangularis) of the inferior frontal gyrus. In the insular area, the IFOF passes deep to the short insular gyri and limen insulae, and deep to the superior and middle temporal gyri,

posterior part of the inferior parietal lobe, and occipital lobe. The claustrocortical fibers pass deep to the part of the cerebral cortex between the supplementary motor area anteriorly and posterior parietal lobe posteriorly. The claustrocortical fibers form the dorsal external capsule, and the IFOF and UF form the ventral external capsule. The AF ventral segment is positioned ventral to the AF dorsal segment in the area above the sylvian fissure, but anterior and dorsal to the dorsal segment below the fissure. The AF ventral segment passes deep to the mid part of the superior and middle temporal gyri, posterior part of the superior temporal gyrus, lower part of the supramarginal gyrus, and post- and precentral and inferior frontal gyri. The AF dorsal segment passes deep to the posterior part of the middle and inferior temporal gyri, lower part of the angular gyrus, post- and precentral gyri, and posterior part of the middle and inferior frontal gyri. AF, arcuate fasciculus; Ang., angular; Ant., anterior; Call., callosum; Caud., caudate; Claustrocort., claustrocortical; Comm., commissure; Corp., corpus; Dors., dorsal; Front., frontal; Glob., globus; Gyr., gyrus; IFOF, inferior fronto-occipital fasciculus; ILF, inferior longitudinal fasciculus; Inf., inferior; LGB, lateral geniculate body; Lim., limiting; Marg., marginal; MdLF, middle longitudinal fasciculus; Mid., middle; Pall., pallidus; Par., parietal; Postcent., postcentral; Precent., precentral; Rad., radiations; SLF, superior longitudinal fasciculus; Sulc., sulcus; Sup., superior; Temp., temporal; Thal., thalamic; UF, uncinate fasciculus; Vent., ventral. (Images courtesy of AL Rhoton, Jr.)

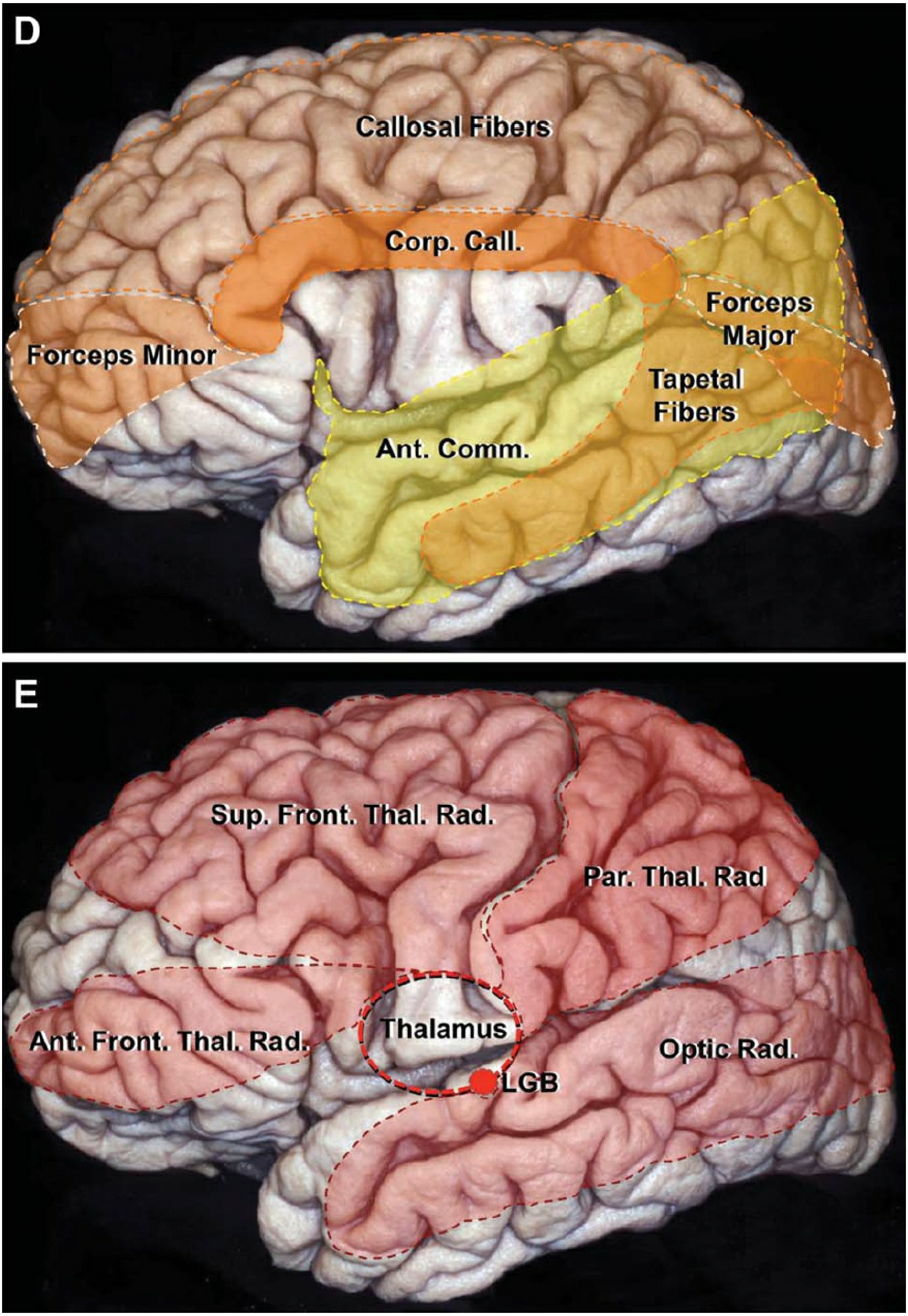
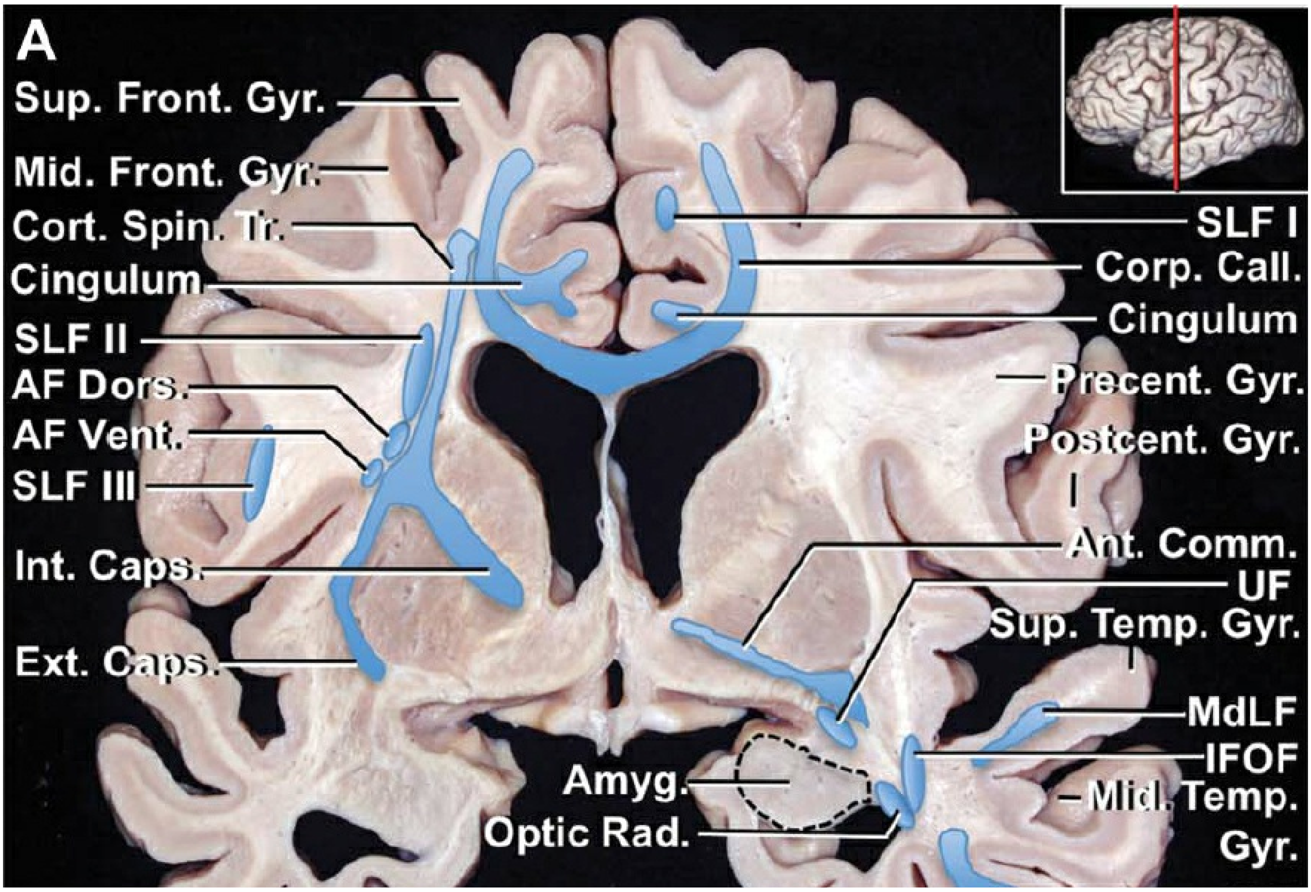


Figure 5 (D–E). D, location of the corpus callosum and the callosal fibers including the forceps minor and major and tapetal fibers and the fibers passing through the anterior commissure. The genu of the corpus

callosum is located deep to the anterior part of the inferior frontal gyrus, the body is located deep to the pre- and postcentral gyri and anterior part of the supramarginal gyrus, and the splenium is located deep to the supramarginal gyrus. The posterior crus of the anterior commissure passes deep to the superior and middle temporal gyri and occipital gyrus. E, site of the thalamic radiations, which connect the thalamus and various cortical areas. The anterior frontal thalamic and the optic radiations pass more horizontally, and the superior frontal and parietal thalamic radiations pursue an oblique course. The optic radiations pass deep to the superior and middle temporal and occipital gyri. AF, arcuate fasciculus; Ang., angular; Ant., anterior; Call., callosum; Caud., caudate; Claustrocort., claustrocortical; Comm., commissure; Corp., corpus; Dors., dorsal; Front., frontal; Glob., globus; Gyr., gyrus; IFOF, inferior fronto-occipital fasciculus; ILF, inferior longitudinal fasciculus; Inf., inferior; LGB, lateral geniculate body; Lim., limiting; Marg., marginal; MdLF, middle longitudinal fasciculus; Mid., middle; Pall., pallidus; Par., parietal; Postcent., postcentral; Precent., precentral; Rad., radiations; SLF, superior longitudinal fasciculus; Sulc., sulcus; Sup., superior; Temp., temporal; Thal., thalamic; UF, uncinate fasciculus; Vent., ventral. (Images courtesy of AL Rhoton, Jr.)



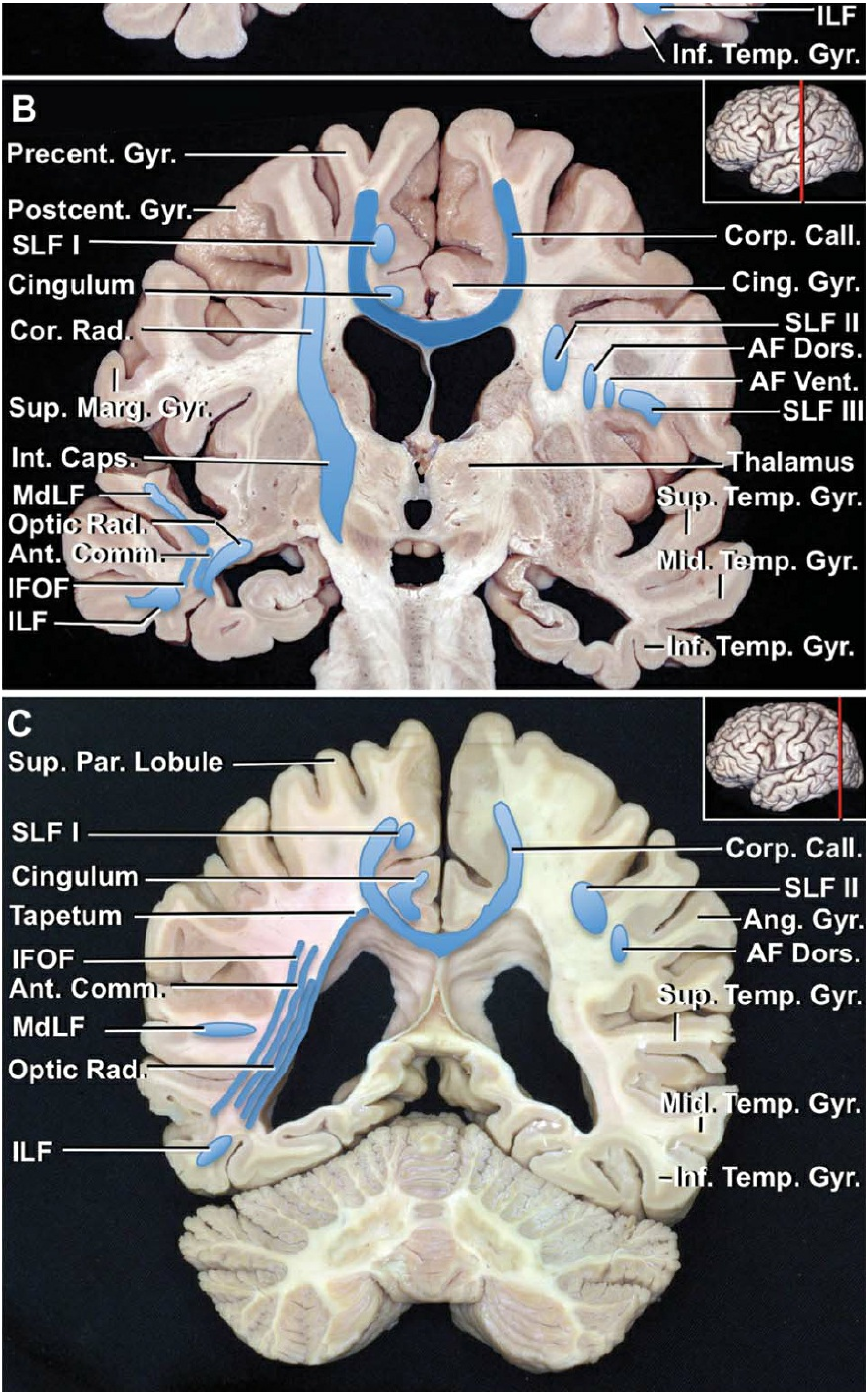

ILF
Inf. Temp. Gyr.
B
Precent. Gyr.
Postcent. Gyr.
SLF I
Cingulum
Cor. Rad.
Sup. Marg. Gyr.
Int. Caps.
MdLF
Optic Rad.
Ant. Comm.
IFOF
ILF
Corp. Call.
Cing. Gyr.
SLF II
AF Dors.
AF Vent.
SLF III
Thalamus
Sup. Temp. Gyr.
Mid. Temp. Gyr.
Inf. Temp. Gyr.
C
Sup. Par. Lobule
SLF I
Cingulum
Tapetum
IFOF
Ant. Comm.
MdLF
Optic Rad.
ILF
Corp. Call.
SLF II
Ang. Gyr.
AF Dors.
Sup. Temp. Gyr.
Mid. Temp. Gyr.
Inf. Temp. Gyr.

Figure 6. Location of fiber tracts in coronal sections. A, anterior view of a coronal section at the level of the precentral gyrus. In the suprasylvian area, in order laterally to medially, the SLF III passes deep to the frontoparietal operculum, and the AF ventral segment is positioned medial to the SLF III and ventrolateral to the AF dorsal segment. The SLF II is located dorsomedial to the AF dorsal segment. The corona radiata, formed by the union of the external and internal capsules above the lentiform nucleus, is situated medial to the AF segments and SLF II. The callosal fibers course medial to the corona radiata above the level of the corpus callosum. The cingulum is positioned above the corpus callosum and medial to the callosal fibers. The SLF I is positioned above the cingulum. In the infrasylvian area, the MdLF passes deep to the surface of the superior temporal gyrus, and the ILF passes deep to the inferior temporal gyrus. The IFOF passes deep to the MdLF and ILF. The fibers in the posterior crus of the anterior commissure are located deep to the lower part of the precentral sulcus on the convexity. The optic radiations are located deep to the superior and middle temporal gyri and lateral to the temporal horn of the lateral ventricle. B, coronal section at the level of the postcentral gyrus. In the suprasylvian area, laterally to medially, are the SLF III, AF ventral and dorsal segments, and SLF II. The corticospinal tract, a part of the corona radiata, is located deep to the association fibers, where it projects vertically downward in the internal capsule. In the infrasylvian area, the IFOF, fibers crossing in the anterior commissure, and optic radiations pass deep to the superior and middle temporal gyri. The ILF passes medial to the inferior temporal gyrus. C, coronal section at the level of the angular gyrus. The AF dorsal segment passes deep to the lower part of the angular gyrus. The SLF II passes deep to the upper part of the angular gyrus. The MdLF passes deep to or through the superior temporal gyrus, and the ILF passes deep to or through the inferior temporal gyrus. Laterally to medially, the fibers of the IFOF, anterior commissure, optic radiations, and tapetum pass lateral to the atrium of the lateral ventricle. The optic radiations pass lateral to the tapetum and inferior two-thirds of the atrium of the lateral ventricle. AF, arcuate fasciculus; Amyg., amygdala; Ang., angular; Ant., anterior; Call., callosum; Caps., capsule; Cing., cingulate; Comm., commissure; Cor.,

corona; Corp., corpus; Cort. Spin., corticospinal; Dors., dorsal; Ext., external; Front., frontal; Gyr., gyrus; IFOF, inferior fronto-occipital fasciculus; ILF, inferior longitudinal fasciculus; Inf., inferior; Int., internal; Marg., marginal; MdLF, middle longitudinal fasciculus; Mid., middle; Par., parietal; Postcent., postcentral; Precent., precentral; Rad., radiata, radiations; SLF, superior longitudinal fasciculus; Sup., superior; Temp., temporal; Tr., tract; UF, uncinate fasciculus; Vent., ventral. (Images courtesy of AL Rhoton, Jr.)

TABLE 2. Functional Role of Fiber Tracts and Associated Disconnection Syndromes[a]

Fiber Tract	Functional Role: Dominant Hemisphere	Functional Role: Nondominant Hemisphere	Disconnection Syndrome
SLF I	Regulation of higher aspect of motor function	Regulation of higher aspect of motor function	Unknown
	Initiation of motor activity[13,17,18]	Initiation of motor activity[13,17,18]	
SLF II	Visuospatial awareness and attention[13,14,19]	Visuospatial awareness and attention[13,14,19]	Spatial working memory disorders (neglect syndrome)[19]
SLF III	Articulatory aspects of language[13,14,17,20-24]	Visuospatial attention, prosody, and music processing[13,14,17,20-24]	Articulatory disorders (dysarthria/anarthria)[13,14,19,20-24]
AF dorsal	Lexical and semantic[b] language processing[25,26]	Prosodic[c] activation of language[25]	Transcortical motor aphasia[25]
AF ventral	Phonological[d] language processing[25,26]	Phonological language processing[25,26]	Phonological paraphasia and repetition disorder[25,26]
MdLF	Attention processing spatial organization and memory of sound[17,28,29,31]	Unknown	There is not any deficit in removal of anterior part[29]
ILF	Object identification, discrimination, and recognition[17,33]	Object identification, discrimination, and recognition[17,33]	No deficit (unilateral damage)[6]
	Indirect semantic aspect of language[34]		Visual agnosia, prosopagnosia (bilateral damage)[33]
IFOF	Semantic aspect of language[34]	Semantic aspect of language[34,42]	Semantic paraphasia[34]
	Visual recognition, integration of the multimodal sensory input[42,43]		
UF	Ventral limbic pathway[33,44]	Ventral limbic pathway[33,44]	Behavioral disturbances[33]
Anterior commissure	Complementary visual processing[33]	Complementary visual processing[33]	None
Cingulum	Dorsal limbic pathway[33]	Dorsal limbic pathway[33]	Behavioral disturbances[33]

[a]SLF, superior longitudinal fasciculus; AF, arcuate fasciculus; MdLF, middle longitudinal fasciculus; ILF, inferior longitudinal fasciculus; IFOF, inferior fronto-occipital fasciculus; UF, uncinate fasciculus.
[b]Lexical semantics: the concepts and meaning of words and vocabulary of words associated with these meanings.
[c]Prosody: modification of the pronunciation of speech to convey additional meaning.
[d]Phonemes: the smallest unit of sound in spoken language.

This study also focused on the relationships of the fiber tracts, from superficial to deep, and their depth from the surface of the cortical gyri (Table 1; Figures 5 and 6). The fiber tracts, from superficial to deep, at the level of the gyri of the frontal lobe were the superior frontal gyrus (corona radiata, callosal fibers, and SLF I), the middle frontal gyrus (SLF II, the dorsal segment of the AF, IFOF, corona radiata, and callosal fibers); and inferior frontal gyrus (SLF III, ventral and dorsal segments of the AF, IFOF, and corona radiata). The fiber tracts deep to the surface of the parietal lobe were the superior parietal lobule (corona radiata, callosal fibers, and SLF I) and the inferior parietal lobule (SLF III, dorsal and ventral segments of the AF, SLF II, MdLF, IFOF, corona radiata, and tapetum). The fiber tracts, from superficial to deep, in the temporal lobe were the superior temporal gyrus (MdLF, UF, IFOF, anterior commissure, optic radiations, and tapetum), the middle temporal gyrus (dorsal and ventral segments of the AF, IFOF, UF, anterior commissure, sagittal stratum, and tapetum); and the inferior temporal gyrus (the dorsal segment of the AF and ILF). The ILF is located below the axial level of the temporal horn of the lateral ventricle. The fiber tracts underlying the occipital gyri were the superior occipital gyrus (ILF, IFOF, anterior commissure, and sagittal stratum, forceps major, and cingulum), the middle occipital gyrus (SLF II [sometimes], ILF, IFOF, and anterior commissure, sagittal stratum, and tapetum); and the inferior occipital gyrus (ILF, IFOF, anterior commissure, sagittal stratum, and forceps major).[9]

DTI has provided a powerful tool for visualizing fiber tracts just as angiography gave us an excellent tool for understanding vascular pathology. However, it is one skill to understand angiography and DTI and another to acquire a 3-D knowledge that allows the arteries or the fiber tracts to be accessed surgically using the hand-eye and cerebral navigation skills of the surgeon. We are entering a stage with fiber tracking similar to that occurring at the time of the introduction of cerebral angiography. Cerebrovascular surgery has been advanced by surgeons gaining an understanding of angiography and using that knowledge to complete microsurgical, endoscopic, and endovascular treatments of vascular pathology. The skills gained in fiber tract dissection when combined with DTI and a 3-D knowledge of the intracerebral fiber tracts will pave the way for advances in parafascicular and intrafascicular surgery. This study combines microsurgical dissection techniques and 3-D photography as an aid to developing the skills and knowledge essential for navigating among the fiber tracts in dealing with cerebral pathology.

DTI has the ability to track the main fiber bundles of the brain. There is still no quantitative DTI study reporting the exact location and depth of each fiber pathway in relation to the overlying gyri. However, comparative analysis of DTI and anatomic dissections have shown a good correlation.[33,76,77] DTI has the ability to demonstrate several fiber pathways in the same image and possibly better display their relationship, as opposed to fiber dissections where some pathways can be displayed only in a stepwise manner. On the other hand, with careful planning, multiple fiber tracts and their relationships can be shown in a single image of a fiber dissection (Figures 2-4).

CONCLUSION

The anatomic findings of this study have been briefly compared with functional data from clinicoradiological analysis and intraoperative stimulation of fiber tracts (Table 2). Better knowledge of the 3-D anatomic organization of the fiber pathways is important in planning safe and accurate surgery for lesions within the cerebrum.

Contributors: Kaan Yagmurlu, MD, Alexander L. Vlasak, and Albert L. Rhoton, Jr, MD

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The Neurosurgical Atlas is honored to maintain the legacy of Albert L. Rhoton, Jr, MD.

REFERENCES

1. Catani M, Dell'acqua F, Bizzi A, et al. Beyond cortical localization in clinicoanatomical correlation. Cortex. 2012;48(10):1262-1287.
2. Catani M, Dell'acqua F, Vergani F, et al. Short frontal lobe connections of the human brain. Cortex. 2012;48(2):273-291.
3. De Benedictis A, Duffau H, Paradiso B, et al. Anatomo-functional study of the temporo-parieto-occipital region: dissection, tractographic and brain mapping evidence from a neurosurgical perspective. J Anat. 2014;225(2):132-151.
4. Duffau H. The "frontal syndrome" revisited: lessons from

electrostimulation mapping studies. Cortex. 2012;48(1):120-131.

5. Rubino PA, Rhoton AL Jr, Tong X, Oliveira Ed. Three-dimensional relationships of the optic radiation. Neurosurgery. 2005;57(4 suppl):219-227.
6. Duffau H, Thiebaut de Schotten M, Mandonnet E. White matter functional connectivity as an additional landmark for dominant temporal lobectomy. J Neurol Neurosurg Psychiatry. 2008;79(5):492-495.
7. Türe U, Yaşargil MG, Friedman AH, Al-Mefty O. Fiber dissection technique: lateral aspect of the brain. Neurosurgery. 2000;47(2):417-426.
8. Fernández-Miranda JC, Rhoton AL Jr, Kakizawa Y, Choi C, Alvarez-Linera J. The claustrum and its projection system in the human brain: a microsurgical and tractographic anatomical study. J Neurosurg. 2008;108(4):764-774.
9. Yaşargil MG. Microneurosurgery. Vol 4A. Stuttgart, NY: Georg Thieme Verlag, Thieme Medical Publishers; 1987:25-39, 50-52.
10. Peltier J, Verclytte S, Delmaire C, Pruvo JP, Godefroy O, Le Gars D. Microsurgical anatomy of the temporal stem: clinical relevance and correlations with diffusion tensor imaging fiber tracking. J Neurosurg. 2010;112(5):1033-1038.
11. Ludwig E, Klingler J. Atlas cerebri humani. Der innere Bau des Gehirns dargestellt auf Grund makroskopischer Präparate. The inner structure of the brain demonstrated on the basis of preparations. Boston, MA: Little, Brown; 1956:1-36.
12. Shimizu S, Tanaka R, Rhoton AL Jr, et al. Anatomic dissection and classic threedimensional documentation: a unit of education for neurosurgical anatomy revisited. Neurosurgery. 2006;58(5):E1000.
13. Makris N, Kennedy DN, McInerney S, et al. Segmentation of subcomponents within the superior longitudinal fascicle in humans: a quantitative, in vivo, DTMRI study. Cereb Cortex. 2005;15(6):854-869.

14. Thiebaut de Schotten M, Dell'Acqua F, Forkel SJ, et al. A lateralized brain network for visuospatial attention. Nat Neurosci. 2011;14(10):1245-1246.
15. Schmahmann JD, Pandya DN, Wang R, et al. Association fibre pathways of the brain: parallel observations from diffusion spectrum imaging and autoradiography. Brain. 2007;130(pt 3):630-653.
16. Maldonado IL, Mandonnet E, Duffau H. Dorsal fronto-parietal connections of the human brain: a fiber dissection study of their composition and anatomical relationships. Anat Rec (Hoboken). 2012;295(2):187-195.
17. Schmahmann JD, Pandya DN. Fiber Pathways of the Brain. Oxford, NY: Oxford University Press; 2006:393-409, 501-530.
18. Petrides M, Pandya DN. Efferent association pathways originating in the caudal prefrontal cortex in the macaque monkey. J Comp Neurol. 2006;498(2):227-251.
19. Thiebaut de Schotten M, Urbanski M, Duffau H, et al. Direct evidence for a parietal-frontal pathway subserving spatial awareness in humans. Science. 2005; 309(5744):2226-2228.
20. Mandonnet E, Duffau H. Understanding entangled cerebral networks: a prerequisite for restoring brain function with brain-computer interfaces. Front Syst Neurosci. 2014;8:82.
21. Martino J, De Witt Hamer PC, Berger MS, et al. Analysis of the subcomponents and cortical terminations of the perisylvian superior longitudinal fasciculus: a fiber dissection and DTI tractography study. Brain Struct Funct. 2013;218(1):105-121.
22. Schiff HB, Alexander MP, Naeser MA, Galaburda AM. Aphemia. Clinicalanatomic correlations. Arch Neurol. 1983;40(12):720-727.
23. Heilman KM, Watson RT. The disconnection apraxias. Cortex. 2008;44(8):975-982.
24. Loui P, Alsop D, Schlaug G. Tone deafness: a new disconnection syndrome? J Neurosci. 2009;29(33):10215-10220.

25. Glasser MF, Rilling JK. DTI tractography of the human brain's language pathways. Cereb Cortex. 2008;18(11):2471-2482.
26. Fernández-Miranda JC, Wang Y, Pathak S, Stefaneau L, Verstynen T, Yeh FC. Asymmetry, connectivity, and segmentation of the arcuate fascicle in the human brain. Brain Struct Funct. Available at: http://link.springer.com/article/10.1007%2Fs00429-014-0751-7. Accessed March 17, 2014.
27. Seltzer B, Pandya DN. Further observations on parieto-temporal connections in the rhesus monkey. Exp Brain Res. 1984;55(2):301-312.
28. Makris N, Papadimitriou GM, Kaiser JR, Sorg S, Kennedy DN, Pandya DN. Delineation of the middle longitudinal fascicle in humans: a quantitative, in vivo, DT-MRI study. Cereb Cortex. 2009;19(4):777-785.
29. De Witt Hamer PC, Moritz-Gasser S, Gatignol P, Duffau H. Is the human left middle longitudinal fascicle essential for language? A brain electrostimulation study. Hum Brain Mapp. 2011;32(6):962-973.
30. Maldonado IL, de Champfleur NM, Velut S, Destrieux C, Zemmoura I, Duffau H. Evidence of a middle longitudinal fasciculus in the human brain from fiber dissection. J Anat. 2013;223(1):38-45.
31. Wang Y, Fernández-Miranda JC, Verstynen T, Pathak S, Schneider W, Yeh FC. Rethinking the role of the middle longitudinal fascicle in language and auditory pathways. Cereb Cortex. 2013;23(10):2347-2356.
32. Catani M, Jones DK, Donato R, Ffytche DH. Occipito-temporal connections in the human brain. Brain. 2003;126(pt 9):2093-2107.
33. Fernández-Miranda JC, Rhoton AL Jr, Alvarez-Linera J, Kakizawa Y, Choi C, de Oliveira EP. Three-dimensional microsurgical and tractographic anatomy of the white matter of the human brain. Neurosurgery. 2008;62(6 suppl 3):989-1026.
34. Duffau H, Gatignol P, Mandonnet E, Peruzzi P, Tzourio-Mazoyer N,

Capelle L. New insights into the anatomo-functional connectivity of the semantic system: a study using cortico-subcortical electrostimulations. Brain. 2005;128(pt 4):797-810.

35. Saur D, Kreher BW, Schnell S, et al. Ventral and dorsal pathways for language. Proc Natl Acad Sci U S A. 2008;105(46):18035-18040.

36. Saur D, Schelter B, Schnell S, et al. Combining functional and anatomical connectivity reveals brain networks for auditory language comprehension. Neuroimage. 2010;49(4):3187-3197.

37. Rhoton AL Jr. The cerebrum. Neurosurgery. 2002;51(4 suppl):S1-S51.

38. Türe U, Yaşargil DC, Al-Mefty O, Yaşargil MG. Topographic anatomy of the insular region. J Neurosurg. 1999;90(4):720-733.

39. Déjerine JJ, Dejerine-Klumpke A. Anatomie des centres nerveux. Paris: J. Rueff; 1895.

40. Makris N, Pandya DN. The extreme capsule in humans and rethinking of the language circuitry. Brain Struct Funct. 2009;213(3):343-358.

41. Dick AS, Bernal B, Tremblay P. The language connectome: new pathways, new concepts. Neuroscientist. 2014;20(5):453-467. Available at: http://nro.sagepub. com/content/20/5/453.long. Accessed December 15, 2013.

42. Sarubbo S, De Benedictis A, Maldonado IL, Basso G, Duffau H. Frontal terminations for the inferior fronto-occipital fascicle: anatomical dissection, DTI study and functional considerations on a multi-component bundle. Brain Struct Funct. 2013;218(1):21-37.

43. Motomura K, Fujii M, Maesawa S, Kuramitsu S, Natsume A, Wakabayashi T. Association of dorsal inferior frontooccipital fasciculus fibers in the deep parietal lobe with both reading and writing processes: a brain mapping study. J Neurosurg. 2014;121(1):142-148.

44. Duffau H, Gatignol P, Denvil D, Lopes M, Capelle L. The articulatory loop: study of the subcortical connectivity by electrostimulation.

Neuroreport. 2003;14(15):2005-2008.

45. Heimer L. Anatomy of Neuropsychiatry: The New Anatomy of the Basal Forebrain and its Implications for Neuropsychiatric Illness. Amsterdam, Boston, MA: Academic Press/Elsevier; 2008:27-99.
46. Surmeier DJ, Mercer JN, Chan CS. Autonomous pacemakers in the basal ganglia: who needs excitatory synapses anyway? Curr Opin Neurobiol. 2005;15(3):312-318.
47. Nieuwenhuys R, Voogd J, van Huijzen C. The Human Central Nervous System: A Synopsis and Atlas. 3rd rev. ed. Berlin, NY: Springer-Verlag; 1988:596.
48. Fox CA, Fisher RR, Desalva SJ. The distribution of the anterior commissure in the monkey, Macaca mulatta. J Comp Neurol. 1948;89(3):245-277.
49. Carpenter MB, Sutin J. Human Neuroanatomy. 8th ed. Baltimore, MD: Williams & Wilkins; 1983.
50. Mesulam MM, Geula C. Nucleus basalis (Ch4) and cortical cholinergic innervation in the human brain: observations based on the distribution of
51. acetylcholinesterase and choline acetyltransferase. J Comp Neurol. 1988;275(2):216-240.
52. Gray H, Williams PL, Warwick R. Gray’s Anatomy. 36th ed. Philadelphia, Edinburgh, NY: Saunders, Churchill Livingstone; 1980:1009-1032.
53. Catani M, Thiebaut de Schotten M. Atlas of Human Brain Connections. Oxford: Oxford University Press; 2012:384-386.
54. Standring SC, Turlough FitzGerald MJ, Collins P. Neuroanatomy. In: Standring S, ed. Gray’s Anatomy: The Anatomical Basis of Clinical Practice. 39 ed. New York, NY: Elsevier, Churchill Livingstone; 2005:227-431.
55. Young PA, Young PH. Basic Clinical Neuroanatomy. 1st ed. Baltimore, MD: Williams & Wilkins; 1997:127-135.

56. Jiménez F, Velasco F, Salín-Pascual R, et al. Neuromodulation of the inferior thalamic peduncle for major depression and compulsive disorder. Acta Neurochir Suppl. 2007;97(pt 2):393-398.
57. Walters CL, Schmidek HH. Surgical management of intracranial gliomas. In: Schmidek HH, Sweet WH, eds. Operative Neurosurgical Techniques: Indications, Methods, and Results. 2nd ed. New York, NY: Grune & Stratton; 1988:431-450.
58. De Benedictis A, Sarubbo S, Duffau H. Subcortical surgical anatomy of the lateral frontal region: human white matter dissection and correlations with functional insights provided by intraoperative direct brain stimulation: laboratory investigation. J Neurosurg. 2012;117(6):1053-1069.
59. Muggleton NG, Juan CH, Cowey A, Walsh V, O'Breathnach U. Human frontal eye fields and target switching. Cortex. 2010;46(2):178-184.
60. Anderson EJ, Jones DK, O'Gorman RL, Leemans A, Catani M, Husain M. Cortical network for gaze control in humans revealed using multimodal MRI. Cereb Cortex. 2012;22(4):765-775.
61. Duffau H. Lessons from brain mapping in surgery for low-grade glioma: insights into associations between tumour and brain plasticity. Lancet Neurol. 2005;4(8):476-486.
62. Baddeley A, Jarrold C. Working memory and Down syndrome. J Intellect Disabil Res. 2007;51(pt 12):925-931.
63. Stuss DT, Knight RT. Principles of Frontal Lobe Function. Oxford, NY: Oxford University Press; 2002:85-96.
64. Krause M, Mahant N, Kotschet K, et al. Dysexecutive behaviour following deep brain lesions—a different type of disconnection syndrome? Cortex. 2012;48(1):97-119.
65. Rech F, Herbet G, Moritz-Gasser S, Duffau H. Disruption of bimanual movement by unilateral subcortical electrostimulation. Hum Brain Mapp. 2014;35(7):3439-3445.
66. Krainik A, Lehéricy S, Duffau H, et al. Role of the supplementary

motor area in motor deficit following medial frontal lobe surgery. Neurology. 2001;57(5):871-878.

67. van Geemen K, Herbet G, Moritz-Gasser S, Duffau H. Limited plastic potential of the left ventral premotor cortex in speech articulation: evidence from intraoperative awake mapping in glioma patients. Hum Brain Mapp. 2014;35(4):1587-1596.
68. Duffau H, Capelle L, Sichez N, et al. Intraoperative mapping of the subcortical language pathways using direct stimulations. An anatomo-functional study. Brain. 2002;125(pt 1):199-214.
69. Vidorreta JG, Garcia R, Moritz-Gasser S, Duffau H. Double dissociation between syntactic gender and picture naming processing: a brain stimulation mapping study. Hum Brain Mapp. 2011;32(3):331-340.
70. Mesulam MM. Behavioural neuroanatomy: large-scale networks, association cortex, frontal syndromes, the limbic system, and the hemispheric specializations. In: Mesulam MM, ed. Principles of Behavioral and Cognitive Neurology. 2nd ed. Oxford, NY: Oxford University Press; 2000:xviii, 540.
71. Rankin KP, Gorno-Tempini ML, Allison SC, et al. Structural anatomy of empathy in neurodegenerative disease. Brain. 2006;129(pt 11):2945-2956.
72. Mega MS, Cummings JL, Salloway S, Malloy P. The limbic system: an anatomic, phylogenetic, and clinical perspective. J Neuropsychiatry Clin Neurosci. 1997;9(3):315-330.
73. Salloway S, Malloy P, Duffy JD. The Frontal Lobes and Neuropsychiatric Illness. 1st ed. Washington, DC: American Psychiatric Pub.; 2001:33-70.
74. Rosen HJ, Allison SC, Schauer GF, Gorno-Tempini ML, Weiner MW, Miller BL. Neuroanatomical correlates of behavioural disorders in dementia. Brain. 2005;128 (pt 11):2612-2625.
75. Petrides M, Pandya DN. Projections to the frontal cortex from the posterior parietal region in the rhesus monkey. J Comp Neurol.

1984;228(1):105-116.

76. Yagmurlu K, Rhoton AL Jr, Tanriover N, Bennett JA. Three-dimensional microsurgical anatomy and the safe entry zones of the brainstem. Neurosurgery. 2014;10(suppl 4):602-619.
77. Holl N, Noblet V, Rodrigo S, et al. Temporal lobe association fiber tractography as compared to histology and dissection. Surg Radiol Anat. 2011;33(8):713-722.
78. Martino J, De Lucas EM. Subcortical anatomy of the lateral association fascicles of the brain: a review. Clin Anat. 2014;27(4):563-569.