Abstract and Introduction

Abstract

Object: In this paper the authors correlate the surgical aspects of deep median and paramedian supratentorial lesions with the connective fiber systems of the white matter of the brain.

Methods: The cerebral hemispheres of 10 cadaveric brains were dissected in a mediolateral direction by using the fiber dissection technique, corresponding to the surgical approach.

Conclusions: This study illuminates the delicacy of the intertwined and stratified fiber laminae of the white matter, and establishes that these structures can be preserved at surgical exploration in patients.

Introduction

Falcine meningiomas; AVMs; cavernomas; intrinsic tumors of the medial frontal, parietal, and occipital lobes, cingulate gyrus, corpus callosum, parapersial region, thalamus, and hypothalamus; and also lesions in the third and lateral ventricles can now be successfully explored and removed via an anterior, middle, or posterior interhemispheric approach, or via a supracerebellar-transtentorial approach, without causing injury.\cite{1-7,9,11-17,20-27} Comprehensive descriptions of the related surgical anatomy and the specific surgical strategy, tactics, and techniques can be found in earlier publications.\cite{22-25}

Dissection

Preparation of Specimens

Ten previously frozen, formalin-fixed human brains were dissected with the aid of an operating microscope by using the fiber dissection technique, beginning at the medial aspect and proceeding to the lateral aspect in a step-by-step fashion.\cite{8,10,18,19} The brains were obtained as fresh autopsy specimens and preserved in 10% formalin solution for at least 2 months. Following the period of fixation, the pia mater, arachnoid mater, and vessels of each specimen were carefully removed under the operating microscope. The brains were washed with running water for several hours to eliminate the formalin, drained, and then refrigerated for 1 week at a temperature of 2 10 to 2 15° C. Before we commenced dissection, the brains were immersed in water and allowed to thaw.

Surgical Tools

The dissection was performed with the aid of an operating microscope, using 4 to 10 3 magnification. During the freezing process, formalin ice crystals form between the nerve fibers, expanding and thus separating the fibers. This freezing process facilitates dissection of the fine fiber bundles in particular. Our primary dissection tools were thin, soft, wooden spatulas with various sized tips (1, 2, 4, and 6 mm) and a surgical suction system. Soft wooden spatulas were used to peel away the fiber bundles along anatomical planes, and high-power suction aided the process.

Mediolateral Dissection of the White Matter

Dissection of the medial aspect of the cerebral hemisphere proceeds as follows (Figure 1A). The midbrain is severed to achieve adequate visualization of the mediobasal temporal region. Dissection begins at the anterior cingulate sulcus and extends posteriorly until the cingulate cortex has been removed. Dissection proceeds along the callosal sulcus and extends from the subcallosal area to the hippocampal sulcus posteriorly. The indusium griseum and lateral and medial longitudinal striae become visible within the callosal sulcus. The indusium griseum is an extension of the hippocampal formation, a fine layer covering the corpus callosum. The indusium griseum extends anteroinferiorly to the paraterminal gyrus, which merges into the diagonal band of Broca, located in the anterior perforated substance. The cingulum is demonstrated around the corpus callosum, and extends as far as the subcallosal area. The connections of the cingulum to the frontal, precentral, postcentral, and precuneal areas are illustrated. The arcuate or U fibers underlying the medial frontoparietal cortex are also displayed. Removing the cortex of the parahippocampal gyrus exposes the inferior arm of the cingulum. The uncus and uncalsulcus are identified, the uncalsulcus being an extension of the hippocampal sulcus. Retracting the cingulum beneath the splenium exposes the tail of the hippocampus and the subinsplenial gyrus (Figure 1B).
Photographs of cadaveric brains showing serial dissections of the medial aspect of the left cerebral hemisphere. A: Medial aspect of the right cerebral hemisphere. Connective arms (arrows) link the cingulate gyrus to gyrus rectus, to anterior, middle, and posterior portions of the medial frontal gyrus, and to the precuneus, and the structure continues as a parahippocampal gyrus. B: The midbrain is removed to achieve sufficient visualization of the mediobasal temporal region. Dissecting the cortex of the cingulate and parahippocampal gyrus demonstrates the whole length of the cingulum and its connections. C: After cutting the medial portion of the corpus callosum, the caudate nucleus in the lateral wall of the lateral ventricle is demonstrated. D: Removal of the choroid plexus, cingulum, and mediobasal temporal region, dissection of the radiating fibers of the corpus callosum, and partial removal of the fornix and amygdala further reveals the stria terminalis, the thalamus, and the hypothalamus, which are covered by the transparent ependyma. E: Partial removal of the ependyma and the caudate nucleus in the lateral ventricle, and dissecting away the subcallosal stratum and the anterior portion of the radiation of the corpus callosum demonstrates cortical extensions of the anterior and superior thalamic peduncles as well as the corona radiata and the intersection of the corpus callosum with the corona radiata. F: Following total removal of the ependyma and caudate nucleus, the tapetum of the corpus callosum and the posterior and inferior thalamic peduncles are demonstrated. G: The tapetum, the stria terminalis, and the amygdala have been dissected away. The thalamus and fibers of the anterior, superior, posterior, and inferior thalamic peduncles as well as the optic radiation on the roof of the temporal horn are demonstrated. Dissecting away the hypothalamus and thalamus demonstrated the column of the fornix and the mammillothalamic tract. H: Removal of the hypothalamus and thalamus with anterior, superior, posterior, and inferior peduncles (the mammillary body and column of the fornix are preserved) demonstrates the lateral portion of the corona radiata and internal capsule. A = amygdala; ac = anterior commissure; acs = anterior calcarine sulcus; af = arcuate fibers; atp = anterior thalamic peduncle (internal capsule); b = body of corpus callosum; bf = body of fornix; cc = corpus callosum; ces = central sulcus; cf = column of fornix; cg = cingulate gyrus; chp = choroid plexus; cin = cingulum; cis = cingulate sulcus; cn = caudate nucleus; cols = collateral sulcus; cp = cerebral peduncle; cr = corona radiata; cs = callosal sulcus; cu = cuneus; e = ependyma; fg = fusiform gyrus; fm = forceps major (radiation of corpus callosum); fmi = forceps minor (radiation of corpus callosum); fo = fornix; g = genu of corpus callosum; gr = gyrus rectus; h = hypothalamus; ic = internal capsule; icc = intersection of corpus callosum with corona radiata; ic1 = frontopontine tract (internal capsule); ic2 = pyramidal tract (internal capsule); ic3 = occipitopontine tract (internal capsule); ic4 = temporopontine tract (internal capsule); ig = indusium griseum; ist = isthmus cinguli; itp = inferior thalamic peduncle (internal capsule); lc = lingual gyrus; m = midbrain; mb = mammillary body; mr = marginal ramus of cingulate sulcus; mt = mammillothalamic tract; oc = optic chiasm; or = optic radiation; ot = optic tract; pb = pineal body; pc = precuneus; pcl = paracentral lobule; pcs = posterior calcarine sulcus; pg = paraterminal gyrus; pos = parietooccipital sulcus; ppc = prepiriform cortex (tip of the parahippocampal gyrus); prcu = precuneus; pt = pulvinar thalami; pt = posterior thalamic peduncle (internal capsule); r = rostrum of corpus callosum; rcc = radiations of corpus callosum; sa = subcallosal area; sas = sagittal stratum; sm = stria medullaris thalami; sn = substantia nigra; sp = splenium of corpus callosum; ss = subcallosal stratum; st = stria terminalis; stp = superior thalamic peduncle (internal capsule); t = thalamus; ta = tapetum of corpus callosum; tp = temporal pole; u = uncus.
After cutting through the medial portion of the corpus callosum, the crus of the fornix and the hippocampal commissure are exposed. The fimbria can be traced to the crus, body, and column of the fornix, and terminates in the mammillary body. The frontal horn, body, and atrial portions of the lateral ventricle with the choroid plexus, as well as the head and body portions of the caudate nucleus are demonstrated (Figure 1C).

The hippocampus, choroid plexus, fimbria, crus, and body portions of the fornix compose the entire anatomy of the lateral ventricle. After further removal of the medial frontoparietal cortex, removal of the cingulum and further dissection of the corpus callosum reveals the radiating fibers of the corpus callosum. The callosal fibers form a major portion of the commissural system and serve to interconnect the hemispheres. The genu portion of these fibers is known as the forceps minor, and the splenial portion is called the forceps major. The uncus is deflected to separate the amygdala from its complex connections, revealing the temporal horn of the lateral ventricle. The hippocampus is dissected free of the collateral eminence to gain entrance in the collateral sulcus. The tail of the hippocampus and the fornix are separated from the choroid plexus along the choroidal fissure. The fornix is incised at the junction of the body and column, and the choroid plexus is removed along the choroidal fissure. The stria terminalis, located between the caudate nucleus and thalamus, connects the bed nucleus of the stria terminalis and parts of the hypothalamus to the amygdala (Figure 1D).

After total removal of the ependyma lining the lateral wall and roof of the lateral ventricle, the posterior portion of the subcallosal stratum and the tapetum of the corpus callosum are demonstrated, both of which were found to be subependymal structures. The tapetum, a subregion of the subcallosal fibers in the splenial region, forms the roof and lateral wall of the atrial portion of the lateral ventricle and sweeps around the temporal horn, thereby separating the fibers of the optic radiation from the temporal horn. Further removal of the caudate nucleus exposes the posterior and inferior thalamic peduncles. During our fiber dissection, identification of the precise location of the border separating the tapetum and the subcallosal stratum eluded us. Nevertheless, we did note a distinct difference between these two structures, and we suspect that the border lies between the body and the atrial portions of the lateral ventricle. In the subcallosal stratum, we were unable to identify a definite fiber system. There was, however, a fiber system clearly present in the tapetum. In addition, we made a significant observation; that the subcallosal stratum has fine, microscopic connections with the superior margin of the caudate nucleus (Figure 1F).

The removal of the frontal horn ependyma (which is a single layer of specialized epithelium lining the ventricles) and the body of the lateral ventricle allows exposure of the head and body of the caudate nucleus and the subcallosal stratum. The subcallosal stratum is a subependymal structure located between the caudate nucleus and the radiations of the corpus callosum. The caudate nucleus is observed to extend along the wall of the lateral ventricle and the tail of the caudate reaches forward to the level of the amygdala. The caudate nucleus has the same soft consistency as the putamen. Removal of the head and body portions of the caudate nucleus reveals the anterior and superior thalamic peduncles. The next step involves dissecting away the anterior portions of the subcallosal stratum and the radiations of the corpus callosum to allow identification of the extensions of the anterior and superior thalamic peduncles to the cortex. These peduncles are the anteromedial portion of the internal capsule, and they connect the frontoparietal regions of the cortex with the thalamus (Figure 1E).

Removal of the anterior, superior, posterior (which includes the optic radiation), and inferior thalamic peduncles together with the thalamus and the lateral geniculate body concludes the dissection and demonstrates the whole corona radiata and the lateral portion of the internal capsule from a medial view, and the cerebral peduncle. These structures are composed of frontopontine fibers, pyramidal tract, and occipitopontine and temporopontine fibers (Figure 1H).

### Surgical Considerations

The striking advances in neurovisualization technology confirm the observations of neuropathologists, neurologists, and neurosurgeons that each type of CNS lesion has a predilection to present in distinct sites in osseous, meningeal, cisternal, parenchymal, ventricular, or vascular compartments. In each of these locations, the lesions may often reach a considerable size without causing any or only discreet signs and symptoms. It can be assumed that a lesion may compress and displace normal brain structures to a greater degree, but lack the capacity to transgress and destroy the unique architecture of the gray and white matter of the CNS. This fact affords us the opportunity to devise and initiate adequate treatment plans.

The main principle of a neurosurgical procedure is always to perform a pure lesionectomy, using tactics to avoid compromising normal homeostasis of the CNS. This surgical principle becomes a challenge to uphold when considering deep, localized, so-called "midline lesions," which may originate from the medial part of the frontal, parietal, or occipital lobe; from the anterior, middle, or posterior parts of the cingulate gyrus; from the paraspinal region (posterior cingulate gyrus, inferior precuneus, and posterior parahippocampal gyrus); corpus callosum; thalamus; hypothalamus; or third and lateral ventricles. All lesions in these locations (tumors, AVMs, and cavernomas) can be explored and removed through an anterior, middle, or posterior interhemispheric, and supracerebellar-infratentorial approach (Figure 2). The specific method of these approaches prevents infliction of harm to the dorsal neopallial areas and to the connective fiber systems of the white matter.
It is an indisputable fact that falcine and callosal lesions, and saccular aneurysms of A2 and A3 segments are explored and removed (or occluded with clips) via an exploration into the interhemispheric fissure. This is considered a routine approach for the majority of midline lesions. Endovascular and gamma knife surgeries have proven effective for some types of tumors and for AVMs of smaller dimensions. Computer-assisted stereotactic, endoscopic, or microsurgical procedures are certainly accurate in targeting these lesions, but transcerebral trajectories to approach a lesion surgically are accompanied by unavoidable injuries to the neopallial cortices and connective fiber systems of the white matter.

**Illustrative Cases**

A few patients with typical deep midline lesions chosen from several hundred cases treated by the senior author (M.G.Y.) at the University of Arkansas for Medical Sciences in Little Rock illustrate the effectiveness of interhemispheric approaches (Figs. 3-12).
Figure 4.

Figure 5.

Case 3. A-C: Preoperative MR images revealing a well-defined lesion in the right anterior lateral thalamic region. D-F: Postoperative MR images obtained after the lesion was removed.

Figure 6.

Case 4. A and B: Preoperative MR images revealing a large tumor originating in the region of the septum pellucidum and extending through the middle of the corpus callosum and interhemispheric fissure to the surface of the left pre- and postcentral gyri. C and D: Postoperative MR images obtained after exploration and complete removal of the tumor.
Figure 7.

Case 5. A-C: Preoperative MR images demonstrating a well-circumscribed lesion within the right precuneus area, with extension into the posterior part of the right parahippocampal gyrus. D-F: Postoperative MR images obtained after exploration and total resection.
Figure 8.

Case 6. A-C: Preoperative MR images revealing a large lesion within the left precuneus and posterior parahippocampal gyrus. D-F: Postoperative MR images obtained after exploration and complete resection of the lesion.
Figure 9.

Figure 10.

Case 1

This 26-year-old woman suffered from simple and complex partial seizures and impairment of her short-term memory. Admission MR images (Figure 3A-C) demonstrated a large tumor occupying the anterior and subcallosal areas of the right cingulate gyrus. The tumor was removed via a frontal interhemispheric approach (Figure 3D-F, postoperative MR images). Histological studies revealed a pilocytic astrocytoma. She had no neurological deficits pre- or postoperatively. Her postoperative course was uneventful. There was a remarkable improvement in her short-term memory difficulties, and she regained her full working capacity.

Case 2

This 10-year-old girl with chronic headaches underwent CT scanning, which demonstrated occlusive hydrocephalus due to a lesion in the third ventricle. After a ventriculoatrial shunt was placed, the lesion was explored and completely removed through a right frontal parasagittal osteoplastic craniotomy, via an anterior interhemispheric transcralosal-transforaminal approach. Histological studies revealed a pilocytic astrocytoma. The patient had no neurological, mental, or endocrine deficits pre- or postoperatively. Nine years of follow up revealed no recurrence of the tumor (Figure 4A-C, preoperative and Figure 4D-F, postoperative MR images).

Case 3

This 12-year-old boy presented with headache after hitting a soccer ball with his head. The admission CT and MR imaging studies revealed a well-defined lesion in the right anterior lateral thalamic region, which was removed via an interhemispheric transcralosal approach. Histological studies revealed pilocytic astrocytoma. The patient's pre- and postoperative neurological and mental status was normal (Figure 5A-C, preoperative and Figure 5D-F, postoperative MR images).

Case 4

This 7-year-old girl experienced progressive weakness distally in her right leg. The admission CT and MR imaging studies revealed a large tumor originating in the region of the septum pellucidum, extending through the middle of the corpus callosum and
interhemispheric fissure to the surface of the left pre- and postcentral gyri. The lesion was explored and completely removed through a left posterior frontal parasagittal craniotomy, and further exploration was performed along the interhemispheric fissure in a supero-inferior dissection (Figure 6A and B, preoperative and Figure 6C and D, postoperative MR images). The postoperative course was uneventful, and the foot process recovered fully within a few months. Histological findings remained inconclusive; the tumor was thought to be either a neurocytoma or an oligodendroglioma.

Case 5
This 42-year-old woman suffered single and complex partial seizures. The admission CT and MR imaging studies demonstrated a well-circumscribed lesion within the right precuneus area, with extension into the posterior part of the right parahippocampal gyrus. With the patient in a sitting position, the lesion was explored and completely removed through a right parietooccipital osteoplastic craniotomy and via a posterior interhemispheric approach (Figure 7A-C, preoperative and Figure 7D-F, postoperative MR images). The histological studies revealed a low-grade oligodendroglioma. The patient was free of neurological and mental deficits pre- and postoperatively, and her visual field is normal. She has regained her full working capacity and has had no seizures.

Case 6
This 36-year-old woman reported difficulty with reading and memory problems. She had right hemianopia and papilledema. The admission MR images (Figure 8A-C) revealed a large lesion within the left precuneus and posterior parahippocampal gyrus. The dorsal part of the tumor had been removed in another hospital. The tumor was completely removed after a second exploration; this was done through a left parietooccipital craniotomy and via an interhemispheric approach with the patient in a sitting position (Figure 8D-F, postoperative MR images). Histological studies revealed a low-grade oligodendroglioma. There were no neurological and mental deficits and no visual field deficits pre- or postoperatively. The patient regained her full working capacity, and has had no seizures.

Case 7
This 25-year-old woman suffered from a headache that increased in intensity over 5 months, fatigue, and short-term memory problems. The admission CT and MR imaging studies demonstrated a compact lesion in the left atrium. With the patient in a sitting position, the tumor was explored through a left parietooccipital osteoplastic craniotomy, via a posterior interhemispheric approach. The dorsomedial extension of the tumor into the posterior part of cingulate gyrus was identified. Through a 10-mm-long incision, the well-encapsulated, very vascularized lesion was completely removed. Histological studies revealed an atypical meningioma. The patient's pre- and postoperative neurological and mental status were found to be normal; in particular no visual field deficit was detected. She regained her full working capacity (Figure 9A-C, preoperative and Figure 9D-F, postoperative MR images). The patient's pre- and postoperative neurological and mental status were found to be normal; in particular no visual field deficit was detected. She regained her full working capacity (Figure 9A-C, preoperative and Figure 9D-F, postoperative MR images).

Case 8
In this 42-year-old woman, who had suffered from typical temporal seizures for a couple of years, admission MR imaging studies (Figure 10A-C) revealed a large, left-sided mediobasal tumor extending into the dorsolateral region of the mesencephalon. The tumor was explored and removed (except for the amygdala area) via a supracerebellar-transtentorial approach (Figure 10D-F, postoperative MR images). The patient's postoperative course was uneventful. Preoperatively and postoperatively she had no neurological or mental deficits, and her visual field was intact. The histological studies revealed a low-grade oligodendroglioma. After surgery, the seizures did not recur and the patient could continue to work at her full capacity.

Case 9
In this 12-year-old girl suffering from a progressive right hemisyndrome but no visual field defect, the admission MR imaging studies revealed a well-circumscribed intrinsic tumor in the left posterior thalamic region (Figure 11A-C). With the patient in a sitting position, the lesion was explored via a left parietooccipital osteoplastic craniotomy and via an interhemispheric approach with the patient in a sitting position. The dorsomedial extension of the tumor into the posterior part of cingulate gyrus was identified. Through a 10-mm-long incision, the well-encapsulated, very vascularized lesion was completely removed. Histological studies revealed a low-grade oligodendroglioma. The dorsomedial extension of the tumor into the posterior part of cingulate gyrus was identified. Through a 10-mm-long incision, the well-encapsulated, very vascularized lesion was completely removed. Histological studies revealed an atypical meningioma. The patient's pre- and postoperative neurological and mental status were found to be normal; in particular no visual field deficit was detected. She regained her full working capacity (Figure 12A-C, preoperative and Figure 12D-F, postoperative MR images).

Case 10
This 45-year-old woman suffered an onset of a right hemisyndrome and homonymous hemianopia. The admission MR images (Figure 12A-C) demonstrated a cavernoma in the left posterior thalamic region. With the patient in a sitting position, this lesion was explored via a supracerebellar-transtentorial approach, and we were able to remove the lesion completely (Figure 12D-F). The histological findings confirmed a cavernoma. Postoperatively the moderate hemiparesis improved remarkably, whereas the visual field deficit remained unchanged.

Discussion
The planning of a neurosurgical procedure incorporates a study of the parenchymal, vascular, cisternal, and ventricular architecture of the brain on MR imaging, MR angiography, MR venography, and serial cerebral angiograms, which are usually analyzed in the axial (base-up > top-down), coronal (anterior-posterior > posterior-anterior), and sagittal view (lateral-medial > mediolateral). Because the lesions are explored with the patient either supine or in a sitting position, but are approached via the interhemispheric fissure in a mediolateral direction, the related fiber system of the white matter is also shown in a mediolateral direction in the dissected cadaveric brains in this study.

Inferiorly extending tumors of the hypothalamus and third ventricle can be explored and resected via a petro-occipital-sylvian and translamina-terminalis approach. Tumors in the posterior part of the third ventricle and the thalamus are approached via the posterior
Lesions in the third ventricle and the anterior two thirds of the lateral ventricle are explored through the anterior or middle part of the interhemispheric fissure, and lesions in the trigonum (atrium) are explored via a posterior interhemispheric approach with the patient in the sitting position. Exploration of the ventricle requires a small incision (10-15 cm) in the commissural fiber system of the corpus callosum.\[^{22-25}\] One exception to this recommendation is when a tumor expands to the surface of the frontal or parietal lobe. This, however, is an extremely rare occurrence.

Dorsal transcerebral approaches traverse neocortical areas, and injuries to cortices and to the complex stratification of associative, commissural, and projection fiber systems are impossible to avoid. Interhemispheric transcallosal approaches are definitely the preferred surgical strategies, offering good access to the lesion, permitting conservation of normal tissue and structures, and resulting in a positive outcome for the patient.

References

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Abbreviation Notes

AVM = arteriovenous malformation; CNS = central nervous system; CT = computerized tomography; MR = magnetic resonance.
Reprint Address

M. Gazi Yasargil, M.D., Department of Neurosurgery, University of Arkansas for Medical Sciences, 4301 West Markham, #507, Little Rock, Arkansas 72205.

M. Gazi Yasargil, M.D., Ugur Ture, M.D., Dianne C. H. Yasargil, R.N., Departments of Neurosurgery, University of Arkansas for Medical Sciences, Little Rock, Arkansas; and Ondokuz Mayis University School of Medicine, Samsun, Turkey
Is There a Superior Occipitofrontal Fasciculus? A Microsurgical Anatomic Study

Türe, Ugur MD; Yasargil, M. Gazi MD; Pait, T. Glenn MD

Department of Neurosurgery, University of Arkansas for Medical Sciences, Little Rock, Arkansas

Received, May 1, 1996. Accepted, January 7, 1997.

Reprint requests: Ugur Türe, M.D., Department of Neurosurgery, University of Arkansas for Medical Sciences, 4301 West Markham, Slot 507, Little Rock, AR 72205.

Abstract

OBJECTIVE: Using a fiber-dissection technique, our aim was to expose and study the myelinated fiber bundles of the brain to achieve a clearer conception of their configurations and locations. During the course of our study, the superior occipitofrontal fasciculus became the focus of our interest. Many publications have defined this as a bundle of association fibers, located between the corpus callosum and the caudate nucleus, that connects the frontal and occipital lobes. By examining this area using fiber dissection, we realized that the descriptions of the anatomy are inadequate; thus, we focused on the elucidation of the anatomic structures of this region and, in particular, that known as the superior occipitofrontal fasciculus.

METHODS: Twenty previously frozen, formalin-fixed human brains were dissected under the operating microscope using the fiber-dissection technique.

RESULTS: On coronal sections of the brain, a structure on the superolateral aspect of the caudate nucleus usually has been identified as the superior occipitofrontal fasciculus. However, our fiber dissections revealed that this structure is the superior thalamic peduncle, that it is composed of projection fibers rather than association fibers, and that it does not interconnect the occipital and frontal lobes.

CONCLUSION: The structures of the brain are better understood when the fiber-dissection technique is used to explore their configurations and locations. The resulting information is especially beneficial for planning strategies and tactics of neurosurgical procedures.

The white matter of the cerebral hemispheres consists of myelinated fiber bundles, called fasciculi, which are divided into three groups: 1) association, 2) commissural, and 3) projection. Association fibers interconnect cortical regions within the same hemisphere. The main association fasciculi are the arcuate fibers, the cingulum, the uncinate fasciculus, the superior and inferior longitudinal fasciculi, and the superior and inferior occipitofrontal fasciculi. The commissural fibers cross the midline and interconnect the two hemispheres. These fiber tracts include the corpus callosum, the anterior commissure, and the hippocampal commissure. Projection fibers connect the cerebral cortex with subcortical regions. These radiating projection fibers form the corona radiata, and, near the rostral part of the brain stem, they form a compact band of fibers known as the internal capsule (3, 11, 23, 33).

We used the fiber-dissection technique to reveal the association, commissural, and projection fibers of the brain. This technique, which involves peeling away the white matter tracts of the brain to display its internal anatomic organization, was the first to allow a true three-dimensional appreciation of the brain. As early as the 17th century, this technique was used to demonstrate many tracts and fasciculi of the brain (4, 6, 9, 17, 21, 22, 29, 31). Since the development of the microtome and histological techniques, fiber dissection has not been extensively used. Klinger (16) cultivated an interest in the fiber-dissection technique and developed an improved method of brain fixation and fiber dissection that now bears his name, Klinger's technique (16, 17, 21). He maintained that dissecting fiber tracts of the white matter was the best method for acquiring an accurate knowledge and understanding of the internal structures of the brain.

During our anatomic study, we were unable to identify the superior occipitofrontal fasciculus. Our analysis of numerous publications revealed inconsistencies in the definitions, locations, and patterns of this fasciculus (1-5, 7, 8, 11, 18, 23, 24, 26, 27, 30, 32). On coronal sections of the brain, a structure 2 to 3 mm in width and situated on the superolateral aspect of the caudate nucleus and lateral to the subcallosal stratum exists. Studies of histological cross sections suggested the possibility that this structure is a collection of association fibers interconnecting the...
frontal and occipital lobes, forming the superior occipitofrontal fasciculus (Fig. 1, A and B) (7, 8, 18, 23, 24, 30, 32). Thus, we focused on the clarification of the anatomic structures of this region.

FIGURE 1. A, coronal section through the center of the third ventricle, the mamillary body, and the hippocampus. In this panel, number 22 is identified as the superior occipitofrontal fasciculus (arrow) (our dissection identified the structure marked 22 as the superior thalamic peduncle), 23, stria terminalis; 32, optic tract; 33, cerebral peduncle; 35, hippocampus (from, Nieuwenhuys R, Voogd J, van Huijzen C: The Human Central Nervous System. Berlin, Springer-Verlag, 1988, p 101, with permission [23]).

B, long association bundles of the right hemisphere in a lateral view. In this schematic figure, number 1 is identified as the superior occipitofrontal fasciculus (arrow) (in our dissection, we observed no fasciculus composed of association fibers following the pattern as shown in 1). 2, site of corona radiata; 3, superior longitudinal fasciculus; 6, outline of insula; 7, inferior occipitofrontal fasciculus; 8, inferior longitudinal fasciculus; 9, site of anterior commissure; 10, uncinate fasciculus (from, Nieuwenhuys R, Voogd J, van Huijzen C: The Human Central Nervous System. Berlin, Springer-Verlag, 1988, p 367, with permission [23]).

MATERIALS AND METHODS
We dissected 20 previously frozen, formalin-fixed human brains under the operating microscope using the fiber-dissection technique of Klingler (16, 17, 21). The brains were removed from the crania no later than 10 to 12 hours postmortem and were fixed in a 10% formalin solution for at least 2 months. To maintain the normal contours of the brain, the basilar artery was ligated and used to suspend the brain in the formalin solution. The specimens were then washed under running water for several hours to remove the formalin and were refrigerated at temperatures ranging from -10 to -15°C for 1 week. Afterwards, they were immersed in water and allowed to thaw. The specimens were then dissected using the operating microscope with 6× to 40× magnification. The primary dissection tools were handmade, thin, wooden spatulas with various tip sizes.

RESULTS

In 16 of the 20 specimens, we dissected the medial aspect of the cerebral hemispheres. After removing the cortex, the hippocampus, the medial portion of the corpus callosum, and the fornix, we demonstrated the entire anatomy of the lateral ventricle (Fig. 2A). The removal of the ependyma (which is a single layer of specialized epithelium lining the ventricles) of the frontal horn and the body of the lateral ventricle allowed the exposure of the subcallosal stratum. The subcallosal stratum is a subependymal structure located between the caudate nucleus and the radiation of the corpus callosum. The head and body of the caudate nucleus were removed to demonstrate the fibers of the anterior and superior thalamic peduncles (Fig. 2B). After total removal of the ependyma of the lateral wall and the roof of the lateral ventricle, we demonstrated the posterior portion of the subcallosal stratum and the tapetum of the corpus callosum, both of which were found to be subependymal structures. The tapetum, a subgroup of callosal fibers in the splenial region, forms the roof and lateral wall of the atrial portion of the lateral ventricle and sweeps around the temporal horn, thereby separating the fibers of the optic radiation from the temporal horn. During our fiber dissection, we could not identify the precise location of the border separating the tapetum and the subcallosal stratum. However, we noted a distinct difference between these two structures, and we suspect that the border lies between the body and atrial portions of the lateral ventricle. In the subcallosal stratum, we could not identify a definite fiber system. For this reason, we prefer to use the nomenclature "stratum" (a layered, sheetlike mass of substance of nearly uniform thickness), to describe this structure rather than "fasciculus," as some authors do (1, 3, 23, 28, 32). There was, however, a fiber system clearly present in the tapetum. Also, we observed that the subcallosal stratum had microscopic connections with the superior margin of the caudate nucleus. We next dissected away the anterior portions of the subcallosal stratum and the radiation of the corpus callosum to allow identification of the extensions of the anterior and superior thalamic peduncles to the cortex (Fig. 2C). After removing the remaining portions of the subcallosal stratum and the caudate nucleus, we dissected away the tapetum, the stria terminalis, and the amygdala, exposing the entire anatomy of the anterior, superior, posterior, and inferior thalamic peduncles as well as the optic radiation on the roof of the temporal horn (Figs. 2D and 3).
labeled. B, after partial removal of the ependyma (e) and the caudate nucleus (cn) in the frontal horn and body of the lateral ventricle, we demonstrated the subcallosal stratum, stratum (ss), the anterior thalamic peduncle (atp), and the superior thalamic peduncle (stp). rcc; radiation of the corpus callosum; st, stria terminalis; f, fornix; t, thalamus. C, after totally removing the ependyma of the lateral wall and roof of the lateral ventricle, dissecting away the anterior portions of the subcallosal stratum (ss) and the radiation of the corpus callosum (rcc), we demonstrated cortical extensions of the anterior thalamic peduncle (atp) and superior thalamic peduncle (stp), as well as the corona radiata (cr), the intersection of the corpus callosum with the corona radiata (icc), the tapetum of the corpus callosum (ta), and the inferior thalamic peduncle (itp). cn, caudate nucleus; st, stria terminalis; f, fornix; t, thalamus; a, amygdala. D, tapetum, subcallosal stratum, caudate nucleus, stria terminalis, and amygdala have been dissected away. The thalamus (t) and fibers of the anterior thalamic peduncle (atp), superior thalamic peduncle (stp), posterior thalamic peduncle (ptp), and inferior thalamic peduncle (itp), as well as the optic radiation (or) on the roof of the temporal horn, are demonstrated. The fibers of the superior thalamic peduncle form an angle (arrow) inferiorly and continue to the thalamus. The change in direction of the superior thalamic peduncle inferiorly is not demonstrated on histological coronal sections. It is clearly shown that there is no fasciculus on the superolateral aspect of the caudate nucleus and lateral to the subcallosal stratum connecting the frontal lobe to the occipital lobe, which has been described in previous publications as being the superior occipitofrontal fasciculus. According to our observations, this structure is the superior thalamic peduncle. cr, corona radiata; icc, intersection of the corpus callosum with the corona radiata; rcc, radiation of the corpus callosum; f, fornix.

FIGURE 3. The medial aspect of the left hemisphere. The anterior and middle portions of the corpus callosum, the ependyma of the lateral ventricle, the subcallosal stratum, the caudate nucleus, the stria terminalis, the fornix (f), and the thalamus (t) have been dissected away. The angle (arrow) of the fibers belonging to the superior thalamic peduncle (stp) are shown. ac, anterior commissure; atp, anterior thalamic peduncle; cr, corona radiata; icc, intersection of corpus callosum with corona radiata; on, optic nerve; pg, parahippocampal gyrus; rcc, radiation of corpus callosum; s, splenium of corpus callosum; sn, substantia nigra.

In the four remaining specimens, we performed coronal sections through the center of the third ventricle. We identified a structure 2 to 3 mm in width, on the superolateral aspect of the caudate nucleus and lateral to the subcallosal stratum. This structure was previously thought to be the superior occipitofrontal fasciculus. Continuing further the dissection of the ependyma of the lateral ventricle, the caudate nucleus, the stria terminalis, and the thalamus, we observed that the fibers constituting this structure formed an angle inferorily, extending to the thalamus and, therefore, belonging to the superior thalamic peduncle (Fig. 4, A and B).
Studies of histological coronal cross sections led to the identification of a structure on the superolateral aspect of the caudate nucleus, which was speculated to be formed by association fibers connecting the occipital and frontal lobes. It was referred to as the "superior occipitofrontal fasciculus" (7, 8, 18, 23, 24, 30, 32). Our serial dissections of 20 brain specimens clearly demonstrated, however, that these fibers are projection fibers (rather than association fibers) belonging to the superior thalamic peduncle, which radiates from the posterior limb of the internal capsule, and also that its fibers form a connection between the ventral thalamic nuclei and posterior frontal and parietal lobes.

**DISCUSSION**

Little is known concerning the relations, courses, and connections of the fibers of the white matter. These fibers are difficult to follow by
Because performing the fiber-dissection technique is relatively difficult and time-consuming, its neglect became almost inevitable after the development of the microtome and histological techniques. During the early part of the 20th century, a few anatomists, such as Johnston (15), Jamieson (14), Hoeve (12), and Curran (4), still preferred the fiber-dissection technique for studying brain anatomy. In 1909, Curran (4) described the inferior occipitofrontal fasciculus using this technique. He stated that one of the limitations of cross-section studies is the inability of these sections to clearly demonstrate acute vertical changes in the direction of the fibers. In 1929, Hultkrantz (13) published an atlas with illustrations of fiber-dissected brains. In 1935, Klingler (16) developed an improved method of brain fixation and fiber dissection that now bears his name. His atlas on fiber dissection, published with Ludwig in 1956, contains detailed anatomic studies of the brain (21). Although his studies were impressive, this technique never became widely used. Illustrations of the internal structure of the brain in current textbooks are usually pictures of sections or schematic drawings. Only a few fiber dissections from earlier textbooks are still reproduced (2, 8, 11, 26, 27, 33).

The superior occipitofrontal fasciculus was described at the end of the 19th century, but its location and pattern have never been clearly defined (1-8, 11, 13, 18, 23, 24, 26, 27, 30, 32). The prevailing consensus is that this fasciculus interconnects the frontal and occipital lobes and passes over the superolateral aspect of the caudate nucleus as association fibers. On coronal sections of the brain, it is identified on the superolateral aspect of the caudate nucleus and lateral to the subcallosal stratum as a structure 2 to 3 mm in width (7, 8, 11, 23, 24, 30, 32).

However, Platzer (27) and De Armond et al. (5), in separate atlases, identified this structure on the coronal sections of the brain as the "superior longitudinal fasciculus." Fix and Punte (8) used the nomenclatures "occipitofrontal fasciculus" and "subcallosal fasciculus" interchangeably in their book. Curran (4) was unable to identify the superior occipitofrontal fasciculus using the fiber-dissection technique. Instead, he discovered and named the "inferior occipitofrontal fasciculus" that interconnects the frontal and occipital lobes in the inferior part of the extreme capsule. Ludwig and Klingler (21), and then Gluhbegovic and Williams (10), demonstrated and referred to the "inferior occipitofrontal fasciculus" but did not mention the "superior occipitofrontal fasciculus." They exposed the superior thalamic peduncle; however, they did not discuss that these fibers appear to compose what others refer to as the "superior occipitofrontal fasciculus" on coronal sections. Ludwig and Klingler (21) also identified what we call the "subcallosal stratum" as the "subcallosal fasciculus." Hultkrantz (13) identified the "subcallosal stratum" as the "subcallosal fasciculus" or the "occipitofrontal fasciculus of Forel." In Dorland's Medical Dictionary (1), the "superior occipitofrontal fasciculus" and the "subcallosal fasciculus" are both defined as "a collection of association fibers lying just internal to the intersection of the internal capsule and corpus callosum, interconnecting the cortex of the occipital and temporal lobes with that of the insula and frontal lobe, and probably comprising a significant part of the tapetum." Hoeve (12) also mentioned a relationship between the "occipitofrontal fasciculus of Forel" and the tapetum. Most likely, he was describing what we call the "subcallosal stratum." Crosby et al. (3) identified what we call the "subcallosal stratum" as the superior occipitofrontal fasciculus or subcallosal fasciculus. Both Parent (26) and Carpenter (2) identified the "inferior occipitofrontal fasciculus" but made no mention of the "superior occipitofrontal fasciculus" in their books. The superior occipitofrontal fasciculus was not mentioned in the current Nomina Anatomica (25), perhaps because of the brevity of the list (the inferior occipitofrontal fasciculus, clearly demonstrated by Curran [4], also did not appear there). Williams et al. (33) did not specifically mention either the superior or inferior occipitofrontal fasciculus. They referred to only the "occipitofrontal fasciculus," but its anatomic description corresponds to that of the "superior occipitofrontal fasciculus." These confusing nomenclatures and descriptions are an indication that this structure is not clearly understood.

Riley (28), in his atlas based on myelin-stained material, used the terms "superior occipitofrontal fasciculus" and "stratum reticulatum coronae radiatae" interchangeably. He stated that this structure is thought by Marburg to represent a thalamocortical radiation. He also mentioned the subcallosal stratum in the same definition with the subcallosal fasciculus, adding that its constituents are not clear. Krieg (18), in 1942, described the superior and inferior occipitofrontal fasciculi as association fibers; however, in 1966, he preferred the term "medio-frontal bundle" instead of "superior occipitofrontal fasciculus" (19). His definitions regarding the mediofrontal bundle and the subcallosal fasciculus (subcallosal stratum) are revealing.

In the angle between capsule and callosum are two bundles not generally understood. The lateral blends with the internal capsule, but its fibers are more nearly horizontal than adjacent capsular ones. This proves to be the projection from the medial thalamic nucleus to the frontal areas. The other tract, subcallosal fasciculus, is not understood at all. It is coextensive with the lateral ventricle, but seems to arise from nowhere.
In 1973, he published his studies on the cerebral fiber systems based on chimpanzee brains (with degeneration-stained preparations) and human newborn, infant, and adult brains (with myelin-stained sections) (20). He concedes the difficulty of interpreting histological techniques, because the axonal pathways "appear to be an inextricable feltwork in myelin stained sections." He recommended experimental studies with monkeys using a degeneration-stained technique to better understand the human brain; however, he also added that the human brain does not follow the same pattern as the monkey's brain. In this study, he renamed the mediofrontal bundle the "juxtacaudate system" because it is complex and difficult to unravel and added that this system must belong to the thalamic radiations.

Our study using the fiber-dissection technique clearly shows that when referring to the coronal section of the brain, the structure on the superolateral aspect of the caudate nucleus and lateral to the subcallosal stratum is not the "superior occipitofrontal fasciculus"; rather, it is the "superior thalamic peduncle" and is, therefore, composed of projection fibers. In our opinion, it has been incorrectly identified and described as the "superior occipitofrontal fasciculus" because of the limitations of cross-section studies, which fail to elucidate the angle taken by these fibers. The superior thalamic peduncle diverges from the posterior limb of the internal capsule, and its fibers form a two-way connection between the ventral thalamic nuclei and rolandic area and adjacent portions of the frontal and parietal lobes (2, 3, 23). Fibers, carrying general somatic sensory signals from the body and head, form part of this radiation and terminate in the postcentral gyrus.

Also, according to some authors, what we call the "subcallosal stratum" is the superior occipitofrontal fasciculus or occipitofrontal fasciculus of Forel (3, 12, 13). We do not agree with those authors. The subcallosal stratum is a subependymal structure that is located in the superolateral wall of the frontal horn and body of the lateral ventricle, and, during our dissection, we could not identify a definite fiber system. The subcallosal stratum disappears near the atrial portion of the lateral ventricle and the tapetum, which is the subgroup of callosal fibers that belong to the commissural system, and appears in the superolateral wall of the lateral ventricle (Fig. 2C). Therefore, what we call the "subcallosal stratum" does not connect the frontal and occipital lobes.

CONCLUSION

Previous anatomic studies relied on histological cross sections and incorrectly indicated that the structure located on the superolateral aspect of the caudate nucleus is composed of association fibers, forming the "superior occipitofrontal fasciculus." Our fiber dissections revealed this structure to be the "superior thalamic peduncle," which is composed of projection fibers.

The fiber-dissection technique confirmed that the "inferior occipitofrontal fasciculus," which Curran (4) described in detail, connects the occipital lobes to the frontal lobes and is, therefore, composed of association fibers. Considering the results of our study that a "superior occipitofrontal fasciculus," as such, does not exist, a more apt nomenclature for the "inferior occipitofrontal fasciculus" would be the "occipitofrontal fasciculus."

Because other anatomic techniques do not consistently provide an accurate perspective of the brain's complex structures, a revival of the fiber-dissection technique of the white matter is strongly advocated. This technique is time-consuming and intricate to perform, but it is beneficial to increasing our knowledge of brain anatomy, which is essential for neurosurgical procedures.

ACKNOWLEDGMENTS

We thank Dianne C.H. Yasargil, R.N., and B. Lee Ligon, Ph.D., for editing the text, Ching Hearnsberger, R.N., for helping to prepare the manuscript, and Grant Sinson, M.D., for recommendations. We are grateful to Professor Ossama Al-Mefty for support and guidance during the completion of this study at the Microsurgical Anatomy Laboratory of the Department of Neurosurgery at the University of Arkansas for Medical Sciences in Little Rock.

This study was presented in part at the 45th Annual Meeting of Congress of Neurological Surgeons, San Francisco, CA, October 1995.

REFERENCES

Türe et al. present an anatomic report of their experience with brain dissection. They emphasize the complexity and confusion of the neuroanatomic nomenclature applied to the human brain and the complexity and confusion of the anatomy itself. Further, they demonstrate the necessity of supplementing gross dissection with a variety of microscopic anatomy-staining techniques to clarify the several origins and terminations of both the association bundles and projection fibers of the cerebral white matter.

The incorporation of a dissection microscope may well stimulate a resurgence of brain dissection using the Klingler (1) technique, at least among neurosurgeons. The reference list provides a compilation of atlases that have artistic renderings of gross dissections of the brain extending over approximately 400 years.

On accepting the findings presented by Türe et al., one is tempted to agree with them that there is not a superior occipitofrontal fasciculus. The structure heretofore given that name is actually the superior thalamic peduncle. However, I think that the authors provide additional evidence for an older view of, and name for, this bundle. The structure that they dissected free of adjacent gray and white matter is or has been known by the name of the occipitofrontal (frontooccipital) fasciculus (2), as well as by several other names, including the "stratum reticulatum coronae radiate of Sachs" (2). Further, this same bundle has already been described as representing a subdivision of the rostral (superior) thalamic peduncle (2) rather than an association fiber bundle, as suggested by its occipitofrontal designation.

Worthy of additional attention is the area Türe et al. call the "subcallosal stratum." This is described in such a way as to allow its interpretation, at least in part, as an occipitofrontal association fiber bundle (2). That the bundle is composed of finely myelinated fibers might account for the authors' inability to trace the fibers using their dissection method. I think the complete picture is yet to be developed.

Charles K. Haun
Neuroanatomist; Los Angeles, California


Türe et al. present an important contribution to neuroanatomy by demonstrating, via a time-consuming technique of fiber dissection along with a series of beautiful pictures and an extensive review of the literature, that the superior occipitofrontal fasciculus does not exist. Because the anatomic descriptions of white matter fasciculi are usually dated from long ago, it would be very interesting and very important for other anatomic centers to use the Klingler (1) fiber dissection technique, resulting in more and more discoveries in this field.

Evandro de Oliveira
São Paulo, Brazil


Key words: Fiber-dissection technique; Inferior occipitofrontal fasciculus; Microsurgical anatomy; Superior occipitofrontal fasciculus; Superior thalamic peduncle

Accession Number: 00006123-199706000-00022
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Version: rel10.2.0, SourceID 1.11354.1.65
Fiber Dissection Technique: Lateral Aspect of the Brain
[Surgical Anatomy and Technique]

Türe, Ugur M.D.; Yasargil, M. Gazi M.D.; Friedman, Allan H. M.D.; Al-Mefty, Ossama M.D.

Department of Neurosurgery (UT), Marmara University School of Medicine, Istanbul, Turkey; Department of Neurosurgery (UT, MGY, OA-M), University of Arkansas for Medical Sciences, Little Rock, Arkansas; and Department of Neurosurgery (AHF), Duke University School of Medicine, Durham, North Carolina

Received, September 22, 1999.
Accepted, March 29, 2000.

Abstract

OBJECTIVE: The fiber dissection technique involves peeling away the white matter tracts of the brain to display its three-dimensional anatomic organization. Early anatomists demonstrated many tracts and fasciculi of the brain using this technique. The complexities of the preparation of the brain and the execution of fiber dissection have led to the neglect of this method, particularly since the development of the microtome and histological techniques. Nevertheless, the fiber dissection technique is a very relevant and reliable method for neurosurgeons to study the details of brain anatomic features.

METHODS: Twenty previously frozen, formalin-fixed human brains were dissected from the lateral surface to the medial surface, using the operating microscope. Each stage of the process is described. The primary dissection tools were handmade, thin, wooden spatulas with tips of various sizes.

RESULTS: We exposed and studied the myelinated fiber bundles of the brain and acquired a comprehensive understanding of their configurations and locations.

CONCLUSION: The complex structures of the brain can be more clearly defined and understood when the fiber dissection technique is used. This knowledge can be incorporated into the preoperative planning process and applied to surgical strategies. Fiber dissection is time-consuming and complex, but it greatly adds to our knowledge of brain anatomic features and thus helps improve the quality of microneurosurgery. Because other anatomic techniques fail to provide a true understanding of the complex internal structures of the brain, the reestablishment of fiber dissection of white matter as a standard study method is recommended.

The segmental and compartmental occurrence of lesions within the central nervous system was emphasized by the senior author (MGY) in his publication Microneurosurgery (40–42). The importance of neuroanatomic laboratory training to learn in detail the cisternal, vascular, and gyral anatomic features and the construction of the white matter, which consists of six compartments and a complex connective fiber system, was stressed (42). A special freezing and dissection technique was developed by Joseph Klingler at the Institute of Anatomy in Basel, Switzerland, in the 1930s (Fig. 1) (19, 20, 23). This technique was learned by the senior author (MGY) in the 1950s (Fig. 2) (15). The knowledge gained from this technique was applied to all of his routine microneurosurgical procedures (40–42). The junior author (UT) developed a great interest in this field while visiting the Department of Neurosurgery, University Hospital, in Zürich, Switzerland, in the 1990s and has since revitalized the dissection technique for connective fibers (36, 37). The intention of this report is to stimulate the young generation of neurosurgeons to acquire proficiency in fiber dissection and to become experts in surgical neuroanatomic features.
FIGURE 1. Lateral view of the internal structures of the left cerebral hemisphere (reprinted from, Ludwig E, Klingler J: *Atlas Cerebri Humani*. Basel, S. Karger, 1956 [23]).
The white matter of the brain consists of myelinated bundles of nerve fibers known as fascicles or fiber tracts. These nerve fibers are divided into three groups, i.e., association, commissural, and projection. Association fibers interconnect neighboring and distant cortical regions within the same hemisphere and are composed of short and long fibers. Arcuate fibers are short association fibers that connect neighboring gyri of the hemispheres. The main long association fibers are the cingulum, the uncinate fasciculus, the occipitofrontal fasciculus, and the superior and inferior longitudinal fasciculi. The cingulum extends from the subcallosal area, continues posteriorly over the dorsal surface of the corpus callosum within the cingulate gyrus as it arcs down around the splenium, and then curves anteriorly into the white matter of the parahippocampal gyrus. The uncinate fasciculus connects the frontal and temporal lobes of the brain, running caudally through the white matter of the frontal lobe, sharply curving ventrally at the limen insula region, and then fanning out to reach the cortex of the anterior portion of the superior and middle temporal gyri (5, 13, 20, 23, 29, 39). The occipitofrontal fasciculus connects the frontal and occipital regions as it passes through the insula and temporal lobe (37). The superior longitudinal fasciculus connects the frontal, parietal, occipital, and temporal lobes around the sylvian fissure. The inferior longitudinal fasciculus is located along the whole length of the temporal and occipital lobes, in part parallel with the temporal horn of the lateral ventricle. The inferior longitudinal fasciculus is a sagittal fiber system that extends into the depths of the fusiform (lateral
Projection fibers connect the cerebral cortex with the brainstem and spinal cord. These radiating projection fibers form the corona radiata and, near the rostral part of the brainstem, they form a compact band of fibers known as the internal capsule, which is medial to the lenticular nucleus and lateral to the caudate nucleus and thalamus (5, 13, 20, 23, 29, 39).

The fiber dissection technique reveals the three-dimensional relationships among the association, commissural, and projection fibers of the brain. This information is invaluable to surgeons performing dissections within the brain parenchyma. This technique, which involves peeling away the white matter tracts to display the internal anatomic organization of the brain, was the first method that provided physicians with a true appreciation of the three-dimensional features of the brain. As early as the 17th century, this technique was used to demonstrate many tracts and fasciculi (1, 3, 4, 7, 10, 11, 22, 25, 28, 30, 32–34, 38). Since the development of the microtome and histological techniques, however, fiber dissection has been neglected. Klingler and colleagues (19, 20, 23) cultivated an interest in the fiber dissection technique and developed an improved method of brain fixation that now bears Klingler’s name (Fig. 1). Despite the development and application of more modern techniques, however, we have failed to improve our understanding of the relationships, course, and connections of the fibers of the brain white matter. This report aims to describe the procedures for this technique, as well as to encourage its revival and promote further study.

MATERIALS AND METHODS

Twenty previously frozen, formalin-fixed, human brains were dissected from the lateral surface to the medial surface in a stepwise fashion, under the operating microscope, using the fiber dissection technique (19, 20, 23). The brains were obtained from fresh autopsy specimens (maximum of 12 h after death) and were fixed in a 10% formalin solution for at least 2 months. The basilar artery was ligated and used to suspend each brain in the formalin solution, so that the brain would maintain its normal contours. After 2 months, the pia mater, arachnoid membrane, and vessels of the specimens were carefully removed, using the operating microscope. The brains were washed under running water for several hours to remove the formalin, drained, and refrigerated for 1 week at a temperature of -10° to -15°C. Before dissection was initiated, the brains were immersed in water and allowed to thaw. The dissection was performed with the aid of the operating microscope, using ×6 to ×40 magnification.

Klingler and colleagues (19, 20, 23) recommended freezing the specimens before dissection, because they thought that the formalin solution did not fully penetrate the myelinated nerve fibers and was observed at higher concentrations between the fibers. When the specimens are frozen, formalin ice crystals form between the nerve fibers, expanding and separating them. The freezing process facilitates the dissection of fine fiber bundles in particular.

Our primary dissection tools were handmade, thin, wooden spatulas with tips of various sizes. The soft wooden spatulas peel away the fiber bundles along the anatomic planes. After dissection has begun, the study may be interrupted overnight or longer, provided that the specimen is maintained in 5% formalin solution between dissection sessions. If dissection is postponed for 1 month or more, it is recommended that the specimen be frozen for at least 12 hours and then thawed, as already described, before the study is recommenced.

A requirement for performing the fiber dissection technique is a thorough knowledge of the gross anatomic features of the brain, which can be gleaned from the available landmark atlases that explain in three-dimensional terms the positions of the inner structures of the brain (10, 19–21, 23, 29, 31, 33). Without this fundamental knowledge, the fine structures of the brain can be inadvertently destroyed during fiber dissection. Before dissection is begun, the course and any variations of the sulci and gyri should be studied.

RESULTS

Dissection begins at the lateral surface of the cerebral hemisphere (Fig. 3). The superior temporal sulcus is a convenient location to begin serial dissections of the lateral aspect of the cerebral hemisphere. The superior temporal sulcus is opened and the cortex is peeled away to expose the underlying white matter. The difference in consistency between the gray and white matter allows differentiation between the two tissue types. Removal of the cortex uncovers the arcuate fibers, which connect the adjacent gyr of the brain. The arcuate fibers are short association fibers of the hemispheres located immediately beneath the cerebral cortex. The majority of the arcuate fibers on the lateral surface of...
the brain are revealed by dissection of the cerebral cortex. This sequence of dissection is to delineate the superior longitudinal (arcuate) fasciculus just beneath the arcuate fibers. Careful removal of the arcuate fibers of the temporal, parietal, and frontal lobes reveals the superior longitudinal fasciculus around the sylvian fissure and insula (Fig. 4). This fasciculus of long association fibers connects the frontal, parietal, occipital, and temporal lobes, presents as a C-shape, and is located deep to the middle frontal gyrus, inferior parietal lobule, and middle temporal gyrus. At this point, the fronto-orbital, frontoparietal, and temporal opercula can be easily lifted to expose the hidden part of the cortex (the insula and the medial surfaces of the opercula). Removal of the fronto-orbital, frontoparietal, and temporal opercula reveals the superior longitudinal fasciculus and the insula.

FIGURE 3. Lateral view of the left cerebral hemisphere before serial dissections. White letters denote sulci and fissures. ang, angular gyrus; ar, ascending ramus of the sylvian fissure; as, acoustic sulcus; asc, anterior subcentral sulcus; ce, cerebellum; cs, central sulcus of Rolando; F1, superior frontal gyrus; F2, middle frontal gyrus; F3, inferior frontal gyrus; f1, superior frontal sulcus; f2, inferior frontal sulcus; hr, horizontal ramus of the sylvian fissure; op, pars opercularis of the inferior frontal gyrus; or, pars orbitalis of the inferior frontal gyrus; O1, superior occipital gyrus; O2, middle occipital gyrus; O3, inferior occipital gyrus; pcg, precentral gyrus; PCS, precentral sulcus; pg, postcentral gyrus; po, pons; ps, postcentral sulcus; pscs, posterior subcentral sulcus; sf, sylvian fissure; smg, supramarginal gyrus; spl, superior parietal lobule; tal, terminal ascending limb of the sylvian fissure; tdl, terminal descending limb of the sylvian fissure; tr, pars triangularis of the inferior frontal gyrus; tts, transverse temporal sulcus; T1, superior temporal gyrus; T2, middle temporal gyrus; T3, inferior temporal gyrus; t1, superior temporal sulcus; t2, inferior temporal sulcus.
The insula is composed of the invaginated portion of the cerebral cortex that forms the base of the sylvian fissure. Total removal of the insular cortex reveals the extreme capsule. The outer layer of the extreme capsule is composed of the arcuate fibers that connect the insula with the opercula in the region of the peri-insular (circular) sulci (Fig. 5). Removal of the extreme capsule reveals the claustrum in the region of the insular apex and the external capsule apparent at the periphery of the claustrum (Fig. 6). The claustrum is a thin, vertically placed lamina of gray matter that is parallel to the putamen. The deeper portion of the extreme capsule and the external capsule consist of fibers of the occipitofrontal and uncinate fasciculi. These fiber bundles are located beneath the basal portion of the insular cortex. The uncinate fasciculus is composed of association fibers of the frontal and temporal lobes that pass through the limen insula and connect the frontal-orbital cortex to the temporal pole. The occipitofrontal fasciculus is a long association fiber bundle that connects the frontal and occipital lobes as it passes through the basal portion of the insula, immediately superior to the uncinate fasciculus. There is no exact delineation between the uncinate and occipitofrontal fasciculi. Both fasciculi form a double fan connected by a narrow isthmus deep to the limen insula. In fact, both fasciculi are incorporated in the same bundle in the region of the limen insula.
FIGURE 5. Lateral view of the left cerebral hemisphere during serial dissection. Total removal of the insular cortex reveals the extreme capsule (exc). The outer layer of the extreme capsule is composed of arcuate fibers that connect the insula with the opercula in the region of the peri-insular (circular) sulci (arrows). cs, central sulcus of Rolando; slf, superior longitudinal fasciculus.

FIGURE 6. Lateral view of the left cerebral hemisphere during serial dissection. Removal of the extreme capsule reveals the claustrum (c) in the region of the insular apex and exposes the external capsule (ec) at the periphery of the claustrum. cs, central sulcus of Rolando; of, occipitofrontal fasciculus; slf, superior longitudinal fasciculus; uf, uncinate fasciculus.

The external capsule is a thin lamina of white substance that separates the claustrum from the putamen. It is joined to the internal capsule at both ends of the putamen and forms a capsule of white matter external to the lenticular nucleus. The external capsule consists mostly of deeper fibers of the occipitofrontal fasciculus. Removal of the inferior aspect of the superior longitudinal fasciculus exposes the entire posterior portion of the occipitofrontal fasciculus. Further dissection of the uncinate and occipitofrontal fasciculi (external capsule) reveals the putamen, which is composed of gray matter substance (Fig. 7). The putamen has a spongy consistency, enabling differentiation from the firmer globus pallidus. At this stage, a suction system can gently remove the putamen and reveal the globus pallidus and the internal capsule at its periphery (Fig. 8). With higher magnification, the strio nigral fibers that pass through the globus pallidus can be identified. These fibers connect the putamen and caudate nucleus to the substantia nigra. The caudolenticular gray matter that passes through the internal capsule and connects the caudate and putamen...
can also be identified. FIGURE 7. Lateral view of the left cerebral hemisphere during serial dissection. Removal of the claustrum and external capsule reveals the putamen (p). Removal of the inferior aspect of the superior longitudinal fasciculus (slf) exposes the posterior portion of the occipitofrontal fasciculus (of). cr, corona radiata; cs, central sulcus of Rolando; uf, uncinate fasciculus.

FIGURE 8. Lateral view of the left cerebral hemisphere during serial dissection. After removal of the putamen, the globus pallidus (gp) and the internal capsule (ic) at its periphery can be observed. Arrows, connections between the putamen and caudate nucleus via the internal capsule. cr, corona radiata; of, occipitofrontal fasciculus; slf, superior longitudinal fasciculus; uf, uncinate fasciculus.

The firmer globus pallidus is excavated to reveal the entire internal capsule and the lateral extension of the anterior commissure (Fig. 9). Removal of the globus pallidus requires skill and patience, to prevent damage to the anterior commissure and the ansa peduncularis. The lateral extension of the anterior commissure passes through the basal portion of the globus pallidus, perpendicular to the optic tract and medial to the uncinate fasciculus, to the temporal pole region. The lateral extensions of the anterior commissure are severed and followed into the temporal lobe. Some fibers of the anterior commissure merge with the uncinate fasciculus at the temporal pole, but most fibers are directed posteriorly.
and eventually merge with the occipitofrontal fasciculus to form the sagittal stratum. Removal of the lateral extension of the anterior commissure and the remainder of the uncinate fasciculus reveals the ansa peduncularis and the optic chiasm. The ansa peduncularis is a complex fiber bundle that curves around the medial edge of the internal capsule and is located within the anterior perforated substance, inferior and parallel to the anterior commissure. It is composed of the amygdaloseptal, amygdalohypothalamic, and amygdaltothalamic fibers. The amygdaloseptal fibers comprise the diagonal band of Broca, which is the extension of the indusium griseum and paraterminal gyrus that connects with the amygdala. The amygdalothalamic fibers are also termed the pedunculus thalami extracapsularis. The remainder of the superior longitudinal fasciculus is dissected away, to reveal the entire corona radiata (Fig. 10). The sagittal stratum consists of the occipitofrontal fasciculus, the posterior thalamic peduncle (which contains the optic radiation), and the fibers of the anterior commissure (23).

FIGURE 9. Lateral view of the left cerebral hemisphere during serial dissection. Removal of the globus pallidus reveals the entire internal capsule (ic) and the lateral extension of the anterior commissure (ac). cr, corona radiata; of, occipitofrontal fasciculus; slf, superior longitudinal fasciculus; uf, uncinate fasciculus.

FIGURE 10. Lateral view of the left cerebral hemisphere during serial dissection. The lateral extensions of the anterior commissure (ac) are
severed and the remainder of the superior longitudinal fasciculus is dissected away. This maneuver reveals the entire corona radiata (cr), the internal capsule (ic), and the ansa peduncularis (ap). *, bed of the nucleus accumbens septi; ac, anterior commissure; ap, ansa peduncularis; ce, cerebellum; cr, corona radiata; ic, internal capsule; on, optic nerve; ot, optic tract; po, pons.

The next step is to dissect the basal surface of the brain. Removal of the semilunar gyrus reveals the cortical nucleus of the amygdala. The amygdala and the anterior two-thirds of the hippocampus and parahippocampal gyrus are dislodged from the prepiriform sulcus and from between the choroidal fissure and the collateral sulcus. The connections between the amygdala and the diagonal band of Broca, the globus pallidus, and the tail of the caudate nucleus can be observed during this dissection. The tail of the caudate nucleus is located on the medial aspect of the roof of the temporal horn, just beneath the ependyma and extending to the amygdala. Removal of the ependyma from the roof of the temporal horn exposes the tail of the caudate nucleus, the inferior thalamic peduncle, and the temporopontine fibers. The inferior thalamic peduncle and the temporopontine fibers are composed of the sublentiform portion of the internal capsule. After total removal of the ependyma of the lateral wall and the roof of the temporal horn, the tapetum of the corpus callosum becomes visible. The tapetum, which is a subgroup of callosal fibers in the splenial region, forms the roof and lateral wall of the atrial portion of the lateral ventricle and sweeps around the temporal horn, thereby separating the fibers of the posterior thalamic peduncle from the temporal horn. The tapetum curves anteriorly into the temporal lobe, extending almost to the tip of the temporal horn just lateral to the tail of the caudate nucleus. Removal of the inferior thalamic peduncle, the temporopontine fibers, and the anterior extension of the tapetum reveals the posterior thalamic peduncle, which consists of the optic radiation. The optic radiation (geniculocalcarine tract) is one of the most complex fiber systems in the human brain. In our opinion, it is often confused with the occiptofrontal, occiptopontine, and temporopontine fibers and with the inferior and posterior thalamic peduncles. Fibers of the tapetum and the anterior commissure are also involved in this problem of false identification. As mentioned previously, the posterior thalamic peduncle includes the optic radiation, but it is almost impossible to clearly demonstrate the actual fibers that comprise the optic radiation (Fig. 11). We also observed that the fibers of the optic radiation extend just posterior to the lateral geniculate nucleus, from the pulvinar thalami to the primary visual cortex in the calcarine region. We think that the classic description of the optic radiation reported by Meyer (27) is incomplete and that further investigation is necessary for an understanding of this complex structure.

Removal of the fibers of the posterior thalamic peduncle exposes the occiptopontine fibers, which belong to the retrolentiform portion of the internal capsule. The course of the occiptopontine fibers is similar to, and can easily be confused with, that of the optic radiation. However, we have observed that the occiptopontine fibers do not extend from the lateral geniculate body or the pulvinar but enter the posterolateral portion of the cerebral peduncle, through which they proceed to the pontine nuclei.

The last stage of dissection reveals the extension of the fibers of the cerebral peduncle to the pons and medulla oblongata. The transverse pontine fibers are dissected from the pontomesencephalic sulcus, and the fibers of the cerebral peduncle can be followed to the pons, where they
interdigitate with the transverse pontine fibers, which connect the pontine nuclei with the middle cerebellar peduncle. The fibers of the frontopontine tract are located in the anterior one-third of the cerebral peduncle. The fibers of the pyramidal tract, located in the middle portion of the cerebral peduncle, extend down to the pons as a series of bundles; in the medulla oblongata, they merge to form the pyramids. The occipitopontine and tempopontine tracts are located in the posterior one-third of the cerebral peduncle and extend to the middle cerebellar peduncle. The optic tract extends to the lateral geniculate body around the cerebral peduncle. Removal of the optic tract exposes the connection between the internal capsule and the cerebral peduncle of the midbrain. At this stage of dissection, corticospinal fiber tracts that extend from the corona radiata to the internal capsule and cerebral peduncle and pass through the pons to the medulla oblongata are observed (Fig. 12).

**FIGURE 12.** Lateral view of the left cerebral hemisphere during serial dissection. After further dissection, the corticospinal fiber tracts are observed from the corona radiata (cr) to the internal capsule (ic) and the cerebral peduncle (cp), passing through the pons (po) to the medulla oblongata. *, bed of the nucleus accumbens septi; ac, anterior commissure; ap, ansa peduncularis; on, optic nerve; pcs, precentral sulcus; sn, substantia nigra.

**DISCUSSION**

Dissection following fiber tracts of the white matter of the brain, to illustrate the internal structures, was the first technique that allowed a true appreciation of the three-dimensional features of the brain. This technique, which is older than the use of histological sections, involves peeling away the white matter tracts of the brain to display its anatomic organization. The fiber dissection technique was one of the first methods used to demonstrate the internal structures of the brain.

Before the development of the microtome and histological techniques, some early anatomists demonstrated many tracts and fasciculi of the brain using this technique. French anatomist Raymond Vieussens (1641–1715) reintroduced the fiber dissection technique, which had been used in the second half of the 17th century by Thomas Willis (1621–1675) and Nicholaus Steno (1638–1686) (24, 38). Vieussens described the fiber dissection technique in detail and in 1685 produced a brain atlas based on this technique (Neurographia Universalis) (38). As judged by modern standards, his specimens seem inferior and the drawings are poor (Fig. 13). Nevertheless, Vieussens is credited with the first description of the pyramids, the inferior olive, the centrum semiovale, and the semilunar ganglion. Following the general method of Constanzo Varolio (1543–1575), Vieussens made some of the first successful attempts to elucidate the internal structures of the brain, demonstrating the continuity of the corona radiata, the internal capsule, the cerebral peduncle, and the pyramidal tracts of the pons and medulla oblongata. He stated,
The white substance of the brain, which herein I shall sometimes call medullary substance and sometimes medulla, is composed of innumerable, connected fibers divided up into many bundles. It appears clearly when the white substance is boiled in the oil, for then it can be readily separated out into the innumerable fibers that, as I said, form it when connected together. So long as these fibers are in their natural site they are so close to one another that there is no perceptible space between them and they constitute a continuous body, just as the fibers within a wooden staff may be separable from one another, but compose a continuous body, that is, the staff.

No similar study appeared in the literature for more than 100 years. In 1802, Sir Charles Bell (1774–1842), an anatomist and surgeon in Edinburgh, published his brain atlas. Having uncommon artistic ability, he illustrated his anatomic publications with his own engravings. In 1810, Johann Christian Reil (1759–1813), a German psychiatrist and neuroanatomist, published an atlas that demonstrated the internal structures of alcohol-fixed brains, as determined using the fiber dissection technique. Reil revealed the tapetum and the optic radiation. His use of alcohol to preserve and harden the brain was a landmark in the history of neuroanatomy. Franz Joseph Gall (1758–1828) and his student J.C. Spurzheim (1776–1832), from Vienna, were the first to demonstrate that the trigeminal nerve was not merely attached to the pons but sent root fibers as far as the inferior olive in the medulla. In addition, they confirmed, with absolute certainty, the medullary decussation of the pyramids. Their anatomic studies, published in 1810, contained several illustrations of good dissections, the best of which demonstrated the corona radiata and the internal capsule from the lateral aspect.
FIGURE 14. Bell’s illustration of the brainstem, depicting the corticospinal tract as it passes from the internal capsule to the pyramidal decussation (reprinted from, Bell C: The Anatomy of the Brain. London, Longman and Co., 1802 [3]).
In 1827, English anatomist Herbert Mayo, who was a student of Bell, published a book that included several of the best illustrations of dissected brains available at that time (Fig. 16) (25). He demonstrated the corona radiata, internal capsule, superior and inferior cerebellar peduncles, fasciculus uncinnatus, fasciculus longitudinalis superior, outer surface of the lenticular nucleus, tapetum, mammillothalamic tractus, and anterior commissure. Two years later, the Italian anatomist Luigi Rolando (1773 – 1831) was the first to accurately portray the cerebral sulci and convolutions, including the central sulcus, which bears his name (34). His atlas contained several drawings of dissected brains. Rolando described and illustrated the continuity of fibers, starting with the medial olfactory stria and proceeding through the subcallosal area and cingulate and parahippocampal gyri, forming a nearly complete circle, and ending in the uncus (Fig. 17). In 1838, German anatomist Friedrich Arnold (1803 – 1890) first demonstrated the frontopontine tract (known as Arnold’s tract), which extends from the frontal cortex through the anterior limb of the internal capsule, via the medial part of the cerebral peduncle, to the pons (1). In 1844, German anatomist and physiologist Karl Friedrich Burdach (1776 – 1847) demonstrated, using the fiber dissection technique, and named the cuneate fasciculus of Burdach (4). The same year, French neurologist Achille L. Foville (1799 – 1878) produced a major work on the nervous system, accompanied by an atlas that illustrated many admirable dissections (10). Although not well known, his atlas is probably the most accurate, the most artistic, and the highest quality publication in the neuroscience literature (Fig. 18). Italian anatomist Bartholomeo Panizza (1785 – 1867) demonstrated the visual pathway from the eye to the occipital cortex, using the fiber dissection technique, in 1855 (30). In 1857, French anatomist Louis Pierre Gratiolet (1815 – 1865), collaborating with his teacher and friend Francois Leuret (1797 – 1851), published an atlas that depicted fiber-dissected brains (Fig. 19) (22). Gratiolet also identified the optic radiation (initially called Gratiolet’s radiation), from the lateral geniculate body to the occipital cortex, in detail. In 1872 in Vienna, Theodor H. Meynert (1833 – 1892), a professor of neurology and psychiatry, refined the relatively crude division of fiber systems of the brain introduced by Gall and, for the first time, used the terms “association” and “projection” fibers in their modern sense (28). His studies of human brains convinced him that the corpus callosum consists primarily of decussating cortical fibers, which course downward to the basal ganglia. Meynert also described the habenulointerpeduncular tract or fasciculus retroflexus (Meynert’s bundle). In 1895, French neurologist Joseph J. Dejerine (1849 – 1917) described the occipitofrontal fasciculus (7). Our study, however, demonstrated that the location he described for this structure was inaccurate (37). In 1896, Swedish anatomist and anthropologist Magnus G. Retzius (1842 – 1919) was the first to use photographs to illustrate brain dissections (33).

FIGURE 17. Rolando’s illustration of the medial surface of the right hemisphere, depicting the fibers of the cingulate and parahippocampal gyri (limbic lobe) (reprinted from, Rolando L: Della Struttura degli Eminusferi Cerebrali. Turin, Memorie della Regia Accademia delle Scienze di Torino, 1829 [34]).
Because the fiber dissection technique is complicated and time-consuming, its neglect was almost inevitable after the development of the microtome and histological techniques. In the early part of the 20th century, a few anatomists preferred fiber dissection for study of the anatomic features of the brain (6, 14, 17, 18). In 1909, E.J. Curran located and described the inferior occipitofrontal fasciculus (6). In 1929, the Swedish anatomist J.W. Hultkrantz published an atlas with illustrations of fiber-dissected brains and described his technique (16). Joseph Klingler (1888–1963), an anatomist in Basel, made the greatest contribution to the fiber dissection technique (19, 20, 23). In 1935, he developed an improved method of brain fixation and a technique that now bears his name (Klingler’s technique) (19). Like others, he dissected formalin-fixed brains with wooden spatulas; however, he froze and thawed the brains before dissection. Freezing helps by separating the fibers. His superb atlas on fiber dissection, containing detailed anatomic studies of the brain, was published in 1956 (Fig. 1) (23). Although his studies were impressive, this technique never became widely used (2, 12, 35). Illustrations of the internal structures of the brain in current textbooks are usually pictures of sections or schematic drawings. Only a few fiber dissections from earlier textbooks are still reproduced (5, 13, 31, 39).

White matter fibers are difficult to follow using histological techniques, and few facts have been assembled regarding the relationships, courses, and connections of these fibers. Available descriptions, which provide a fairly complete account of these connections, are based largely on experimental studies in subhuman primates and are not necessarily applicable to human subjects (29, 39). While examining the white matter of the brain, we realized that current descriptions of the anatomic features are inadequate. For example, we are now aware that the superior occipitofrontal fasciculus, which was known as a bundle of association fibers located between the corpus callosum and the caudate nucleus, connecting the frontal and occipital lobes, does not exist (37). We think, therefore, that detailed studies using the fiber dissection technique have the potential to reveal many interesting findings, which will increase our knowledge and enhance microneurosurgical techniques. We are aware that our comprehension of the detailed and gross anatomic connections of the human brain is incomplete. For example, we continue to base our understanding of the optic radiation on the classic description provided by Meyer (27), although we already know that this description is far from adequate and requires further study (8, 9).
Our contribution to improving the technique of fiber dissection involves the use of the operating microscope to study the details of the fiber systems (36, 37). However, the technique is limited because the fibers of the brain have complex relationships. The demonstration of one fiber system often results in the destruction of other fiber systems. Combining histological techniques with the fiber dissection technique could improve our understanding and prevent misinterpretation of the complex anatomic features of structures. The advantages of the individual techniques would complement each other and eliminate the disadvantages. The revival of the fiber dissection technique and its incorporation into neurosurgical education, especially as preparation for treating patients with intrinsic brain tumors, arteriovenous malformations, or epilepsy, should be considered.

ACKNOWLEDGMENTS

We thank Dianne C.H. Yasargil, R.N., for editing the text and Ching Hearnsberger, R.N., for helping prepare the manuscript.

REFERENCES

This article illustrates an anatomic detail of the organization of the hemispheres and is an interesting addition to the usual neurosurgical literature. It is an example of one of the strengths of Neurosurgery—enlarging the scope of noteworthy facts with which a neurosurgeon should be familiar. In this article and previous articles describing the same technique (1, 2), I found surgery of the temporal lobe to treat epilepsy interesting. The three-dimensional information available from these specimens is extremely useful compared with the studies of these fiber bundles in the atlas and textbooks.

Johannes Schramm

Bonn, Germany


One of the hidden strengths of this important anatomic contribution lies in its ability to further define pathways of glioma dissemination so commonly seen throughout the white matter tracts. The myelinated fascicles or fiber tracts serve as a substrate for neoplastic cells to invade...
adjacent territories. This occurs via association, commissural, and projection pathways and helps to explain the increasing phenomena of gliomatosis cerebri and multifocality. For example, most insular-based gliomas have components in the temporal and frontal lobes. The detailed demonstration of the uncinate fasciculus clearly documents how this takes place. This fasciculus must be identified and entered, underlying the middle cerebral artery bifurcation, during removal of insular gliomas.

Our knowledge of subcortical functional pathways continues to be deficient, and, unfortunately, an anatomic study such as this cannot provide the missing pieces to the puzzle. Notwithstanding, this is a valuable anatomic study using the fiber dissection technique, which will serve as an excellent substrate to aid in our understanding of these critical pathways during surgery and to explain the pathophysiology of certain disease states that we encounter on a daily basis.

Mitchel S. Berger
San Francisco, California

This is an unusual and interesting article, describing an older anatomic technique that is perhaps underappreciated today. Türe et al. present a description of the fiber dissection technique, a “tour” of hemispheric fiber tract anatomy using the technique, and a fascinating historical account.

This is not a quantitative description of fiber tracts based on their investigation; however, it does provide a better appreciation for the three-dimensional, nonlinear organization of the brain and its importance to neurosurgery. This is sufficient reward for the reader; however, if one also is left with the temptation to visit the anatomy or pathology department and try the technique, à la Willis, Bell, Reil, Gall, Rolando, and Meynert, that is icing on the cake.

David W. Roberts
Lebanon, New Hampshire

Key words: Fiber dissection technique; Microsurgical anatomy; White matter

Accession Number: 00006123-200008000-00028

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Version: rel10.2.0, SourceID 1.11354.1.65
The Arteries of the Corpus Callosum: A Microsurgical Anatomic Study

Türe, Ugur M.D.; Yasargil, M. Gazi M.D.; Krisht, Ali F. M.D.

Department of Neurosurgery, University of Arkansas for Medical Sciences, Little Rock, Arkansas

Received, February 22, 1996. Accepted, June 14, 1996.

Reprint requests: Ugur Türe, M.D., Department of Neurosurgery, University of Arkansas for Medical Sciences, 4301 West Markham, Slot 507, Little Rock, Arkansas 72205.

Abstract

OBJECTIVE: The corpus callosum is the major commissural pathway connecting the hemispheres of the human brain. It is particularly important, because various tumors and vascular lesions can be located in and around the corpus callosum, and it is a route through which pass several surgical approaches. Performing accurate surgery in this region and avoiding damage to normal structures require that the neurosurgeon have adequate knowledge of the anatomy of the intricate blood supply to this area.

METHODS: In 20 cadaver brains, the arteries of the corpus callosum were examined under the operating microscope, with particular attention to the origin, course, anastomoses, number, and caliber of the arteries.

RESULTS: In all specimens, the pericallosal and posterior pericallosal arteries were found to be the main sources of blood supply to the corpus callosum. In 80% of the specimens, the anterior communicating artery gave rise to either a subcallosal artery or a median callosal artery, each of which made a substantial contribution to the blood supply of the corpus callosum. A detailed examination of the anatomic features of all the main arteries of supply revealed anastomoses within the callosal sulcus that formed the pericallosal pial plexus. This network supplied the corpus callosum, the radiation of the corpus callosum, and the cingulate gyrus.

CONCLUSION: Familiarity with the details of the vascularity of the corpus callosum is crucial when performing surgery in this region. The additional, significant data described expands the knowledge of this anatomy, which can enhance the surgeon's ability to accomplish a more accurate and successful exploration.

The corpus callosum is the major transverse commissure connecting the cerebral hemispheres. The exact functional role of the corpus callosum in interhemispheric communication is not well understood, although some knowledge is available concerning potential functional disturbances (e.g., the disconnection syndrome that can arise from injury to the corpus callosum)(4, 30).

A review of the literature yields only very general descriptions of the blood supply of the corpus callosum. The studies indicate that the main blood supply originates from the anterior cerebral artery (ACA) and the posterior cerebral artery (PCA)(2, 3, 5, 9-20, 22, 23, 25-29, 32-36). Only a few articles described this special anatomy in detail (12, 17, 24, 31). In a landmark article, Huang and Wolf (12) described the angiographic features of the pericallosal cistern and defined the pericallosal pial plexus. Later, Perlmutter and Rhoton (24), Malobabic et al. (17), and Wolfram-Gabel et al. (31) described the anatomic features of the pericallosal region. Because exploration of the corpus callosum is an integral part of several neurosurgical procedures, a knowledge of the detailed anatomy of the corpus callosum, especially its blood supply, is essential for performing successful neurosurgical procedures in this area (1, 6, 21, 25, 28, 34, 35).

Anatomy of the corpus callosum

The corpus callosum is divided anatomically into four parts: 1) rostrum, 2) genu, 3) body, and 4) splenium. The rostrum and genu form a connection between the frontal lobes, predominantly at their anterior portion, and comprise the floor and anterior wall of the frontal horn in each lateral ventricle. The fibers radiating laterally in both hemispheres form the forceps minor. The body of the corpus callosum connects the posterior portion of the frontal lobes, as well as the parietal lobes, and constitutes the roof of the body of the lateral ventricles. The splenium, the most posterior portion of the corpus callosum, connects the regions of the temporal and occipital lobes. The radiating fibers of the splenium form the forceps major. A subgroup of fibers that connect in the splenial region sweep laterally and inferiorly to form the roof and lateral wall of the
atrial portion of the lateral ventricles; they also sweep around the temporal and occipital horns. This subgroup of fibers, called the tapetum, separates the fibers of the optic radiation from the temporal horn (4, 28, 30)(Fig. 1)

FIGURE 1. Medial surface of the right cerebral hemisphere. The left A1 and A2 segments (white arrowheads) of the ACA and the midbrain (m) have been cut. The photograph shows portions of the corpus callosum, its adjacent structures, and segments of the ACA and PCA. The subcallosal artery (black arrowhead) arises from the ACoA and supplies the rostrum (R) and genu (G) of the corpus callosum in the midline. The A2 segment of the pericallosal artery courses in the subcallosal area (sa) with an S-shaped configuration. The A3 through A5 segments course in the callosal sulcus and branch into the genu, body (B), and splenium (S) of the corpus callosum. The distal type of posterior pericallosal artery (white arrow) arises from the precuneal branch of the parieto-occipital artery and anastomoses with the posterior extension (black arrow) of the A5 segment within the callosal sulcus in the splenial region. ac, anterior commissure; cg, cingulate gyrus; cs, cingulate sulcus; f, fornix; h, hypothalamus; pb, pineal body; pc, precuneus; sp, septum pellucidum; tv, third ventricle.

The fasciolar gyrus, which is an extension of the dentate gyrus, spreads out to become a thin gray layer representing a vestigial convolution, the indusium griseum or supracallosal gyrus, that covers the superior surface of the corpus callosum. Imbedded in the indusium griseum are two slender bands of myelinated fibers, the medial and lateral longitudinal striae, that constitute the white matter of this vestigial convolution. The indusium griseum and the longitudinal striae extend over the entire length of the corpus callosum, pass over the genu, and become continuous with the paraterminal gyrus and the diagonal band of Broca (4, 30). Duvernoy (7) suggested that the indusium griseum is an extension of the cornu ammonis rather than of the dentate gyrus. In either situation, it belongs to the archipallium, a remnant of an extension of the hippocampal formation.

Segments of the ACA and PCA

The ACA and PCA are divided anatomically into various segments. They are classified according to anatomic and functional considerations that will be further described in succeeding sections (Fig. 1).

The ACA is divided in the following manner. The portion extending from the internal carotid artery to the anterior communicating artery (ACoA), is designated the A1 segment. The portion distal to the ACoA is referred to as the pericallosal artery (or the distal ACA) and is subdivided into four segments, A2 through A5. The A2 segment extends from the ACoA to a region between the rostrum and genu of the corpus callosum. The A3 segment courses around the genu to the rostral part of the body of the corpus callosum. The A4 and A5 segments are the continuation of the pericallosal artery along the superior surface of the corpus callosum. In the lateral view, an imaginary line parallel to and just behind the coronal suture represents the demarcation point between the A4 and A5 segments (8, 13, 24, 27, 34).

The PCA is divided into four segments: the P1 segment, which originates at the basilar tip and ends at the junction with the posterior communicating artery (PCoA); the P2 segment, which begins at the junction with the PCoA and runs within the ambient cistern; the P3 segment, which is located in the region of the quadrigeminal cistern; and the P4 segment, which comprises the posterior extension of the PCA and...
MATERIALS AND METHODS

Twenty brains from human cadaver craniums were used for this microsurgical anatomic study. The internal carotid arteries and the vertebral arteries were dissected at the neck and then cannulated. Saline irrigation was used to wash out any residual luminal clots. After a satisfactory collateral flow across the circle of Willis was established, both the carotid and the vertebral arteries were perfused with red-colored latex. The calvarium and dura were opened to allow the cadaver craniums, as well as the brains, to be fixed in a 10% formaldehyde solution to prepare them for microdissection. After a minimum of 1 month, the brains were removed from the craniums, with special care taken to cut the carotid and vertebral arteries proximally.

The various anatomic features of the corpus callosum, as well as its vascularity, were studied using an operating microscope with ×6 to ×40 magnification. Many details, including the origin, course, anastomoses, number, and caliber of the arterial branches involved in the blood supply of the corpus callosum, were carefully examined. The data were recorded and analyzed.

RESULTS

This study verified that the corpus callosum receives its blood supply from three main arterial systems: 1) the ACoA, 2) the pericallosal artery, and 3) the posterior pericallosal artery.

The ACoA

The ACoA, which connects both A1 segments of the ACA, was found to be located 1 to 9 mm (average, 4 mm) from the anterior aspect of the lamina terminalis. The ACoA gave rise to perforator branches in all of our specimens. Their number ranged between 1 and 6 (average, 2.5), and the diameters ranged from 0.15 to 2.1 mm (average, 0.37 mm). These branches were divided into three subgroups: 1) the hypothalamic artery (which did not supply the corpus callosum), 2) the subcallosal artery, and 3) the median callosal artery. In 80% of the specimens, either the subcallosal artery or the median callosal artery was present and contributed to the blood supply of the corpus callosum, especially to the anterior portion. These two arteries were never found to arise together from the ACoA. When either one was present, it occurred as a single artery, always as the dominant branch arising from the ACoA (Fig. 2, A-C).
FIGURE 2. Anatomic variations of the branches arising from the ACoA seen in sagittal (A, C, E, G) and horizontal (B, D, F, H) planes. A and B, the hypothalamic artery (open arrow) arises from the ACoA and supplies the anterior portion of the hypothalamus, the paraterminal gyrus, the subcallosal area, the column of the fornix, and the medial portion of the anterior commissure. In no instance did it supply the corpus callosum. In 20% of the specimens, the ACoA gave rise to only hypothalamic arteries. C and D, the subcallosal artery (open arrow) supplies the same area as the hypothalamic artery and, in addition, the medial portions of the rostrum (R) and genu (G) of the corpus callosum. It was present in 50% of the specimens and always as a single dominant artery. E through H, the median callosal artery follows the same course as
that of the subcallosal artery and supplies the same structures except that its distal extension reaches the body (B) and frequently even the splenium (S) of the corpus callosum. Two anatomic variations were recognized at its distal extension: the classical type (open arrow) occurred in 25% of the specimens (E and F); the hemispheric type (open arrow) occurred in 5% of the specimens (G and H).

The hypothalamic arteries were small perforator branches that arose from the posteroinferior aspect of the ACoA and supplied the anterior portion of the hypothalamus, the paraterminal gyrus, the subcallosal area, the column of the fornix, and the medial portion of the anterior commissure. The number ranged from 0 to 5 (average, 1.8), and the diameter varied between 0.15 and 0.5 mm (average, 0.23 mm). They arose from the ACoA in 85% of the specimens; in 20% of the specimens, the ACoA gave rise to only the hypothalamic arteries; in 40%, the hypothalamic arteries were associated with the subcallosal artery; and in 25%, they were associated with the median callosal artery. In the remaining 15% of the specimens, the hypothalamic arteries arose from the subcallosal artery or the median callosal artery. In none of the specimens did the hypothalamic artery supply branches to the corpus callosum (Figs. 2A, 3, A and B, and 11 and Table 1).

FIGURE 3. Medial surface of the right cerebral hemisphere. The left A1 and A2 segments of the ACA (white print) have been cut. A, a photograph showing the territory of the hypothalamic arteries (white arrow) and subcallosal artery (black arrow) that arise from the ACoA. The subcallosal artery contributes to the blood supply of the medial portions of the rostrum (R) and genu (G) of the corpus callosum. It was present in 50% of the specimens and always as a single dominant artery. B, a photograph showing the territory of the hypothalamic artery (white arrow) and the origin of the hemispheric type of median callosal artery (cut end) (black arrow) that arise from the ACoA. The forceps retract the cut end of the left A2 segment. AC, anterior commissure; CG, cingulate gyrus; CP, choroid plexus; F, fornix; H, hypothalamus; LT, lamina terminalis; LV, lateral ventricle; MB, mamillary body; PG, paraterminal gyrus; SA, subcallosal area; SP, septum pellucidum.

<table>
<thead>
<tr>
<th>Arterial Branches</th>
<th>Diameter (mm)</th>
<th>Number</th>
<th>Occurrence (Brains)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
<td>Average</td>
<td>Number</td>
</tr>
<tr>
<td>Hypothalamic</td>
<td>0.15–0.5</td>
<td>0.23</td>
<td>0–5</td>
</tr>
<tr>
<td>Subcallosal</td>
<td>0.4–0.6</td>
<td>0.5</td>
<td>0–1</td>
</tr>
<tr>
<td>Median callosal</td>
<td>0.4–2.1</td>
<td>0.9</td>
<td>0–1</td>
</tr>
</tbody>
</table>

TABLE 1. Characteristics of Branches from the Anterior Communicating Artery
The subcallosal artery was a major contributor to the blood supply of the medial portions of the rostrum and genu of the corpus callosum. It also supplied the same area fed by the hypothalamic arterial branches, as well as the anterior portions of the cingulate gyrus and the septum pellucidum. It usually coursed posteriorly toward the region of the lamina terminalis, curved superiorly to reach the rostrum, and terminated at some point along the genu in the midline. It was observed in 50% of the specimens and always presented as a single dominant artery (in 40% of the specimens, it arose from the ACoA along with the hypothalamic arteries; in 10%, it was the only artery arising from the ACoA). Its diameter ranged between 0.4 and 0.6 mm (average, 0.5 mm) (Figs. 1, 2C and D, 3A, and 11 and Table 1).

The median callosal artery was present in 30% of the specimens, always as the dominant artery arising from the ACoA, either along with the hypothalamic arteries (25%) or as a single artery (5%). Its diameter ranged from 0.4 to 2.1 mm (average, 0.9 mm). This artery followed the same course as that of the subcallosal artery and supplied the same structures, except that its distal extension reached the body and frequently even the splenium of the corpus callosum. Two anatomic variations were recognized at its distal extension, the classical and the hemispheric types. The classical type occurred in 25% of the specimens (in 5% of the specimens, the artery terminated at a point somewhere along the body of the corpus callosum in the midline; in 15%, it terminated in the medial longitudinal striae at the splenium; and in the remaining 5%, it anastomosed with the posterior pericallosal artery at the splenium). The hemispheric type occurred in only one specimen (5%), and in this instance, the median callosal artery was very enlarged (with a diameter of 2.1 mm). It played a dominant role, functioning virtually as a third pericallosal artery. It gave rise to branches supplying the rostrum, the genu, and the body of the corpus callosum and to large cortical branches that supplied the medial aspects of the frontal and parietal lobes (Figs. 2E-H and 3B and Table 1).

Pericallosal artery

The pericallosal artery ascended in the lamina terminalis cistern, passed between both hemispheres along the interhemispheric fissure, entered the callosal cistern, made a wide arc around the genu, and coursed posteriorly on the superior aspect of the corpus callosum. The average
diameter of the pericallosal artery at its origin was similar on both the right (average, 2.6 mm) and left (average, 2.5 mm) sides. The A2 segment of the pericallosal artery coursed in the subcallosal area, generally in an S-shaped configuration. The A3 through A5 segments coursed in the callosal sulcus in 60% of the hemispheres. In a further 32.5% of the hemispheres, they followed an irregular course, and at least one of the segments coursed in the cingulate sulcus. In the remaining 7.5% of the hemispheres, the A3 through A5 segments coursed in the cingulate sulcus and were never involved with the corpus callosum (Fig. 4, A-C). Furthermore, in 10% of the hemispheres, the A4 segment crossed the midline and supplied portions of the opposite hemisphere.

In the instances where the A5 segment coursed in the callosal sulcus (65%), its posterior extension followed a cork-screw-like tortuosity, anastomosed with the posterior pericallosal artery in the splenial region, and formed the dense portion of the pericallosal pial plexus within the callosal sulcus (Figs. 5D, 10, and 11). Usually, some of the branches arising from this network circled around the splenium and joined the tela choroidea of the third ventricle, where they anastomosed with branches of the medial posterior choroidal arteries. In 5% of the hemispheres, this extension continued anteriorly as far as the foramen of Monro.

FIGURE 4. Anatomic variations in the course pattern of the pericallosal artery. A, in 60% of the hemispheres, the A3 through A5 segments course in the callosal sulcus (CS). B, in an additional 32.5% of the hemispheres, they follow an irregular course, and at least one of the segments runs in the cingulate sulcus (figure shows three variations [I-III]). C, in the remaining 7.5% of the hemispheres, the A3 through A5 segments course in the cingulate sulcus (CS) and are never involved with the corpus callosum.
FIGURE 5. Branches of the pericallosal artery that supply the corpus callosum. A, a photograph showing the body of the corpus callosum (B) after an interhemispheric approach. Forceps retract the left pericallosal artery to show the origin of the callosal artery (arrow), which arises from the left A4 segment and directly supplies the superficial surface of the corpus callosum in the midline, without giving branches to the depths of the callosal sulcus. B, the medial surface of the right cerebral hemisphere. After partial removal of the cingulate gyrus (CG), the callosal sulcus is revealed. Forceps retract the right pericallosal artery. The cingulocallosal arteries (arrows) arise from the inferolateral aspect of the pericallosal artery, run laterally into the callosal sulcus, and form a portion of the pericallosal pial plexus. B, body of corpus callosum; SP, septum pellucidum. C, the medial surface of the right cerebral hemisphere. After partial removal of the cingulate gyrus (CG), the callosal sulcus is revealed. The pericallosal artery courses in the cingulate sulcus (CS). The long callosal artery (arrow) arises from the pericallosal artery, supplies the body (B) and splenium (S) of the corpus callosum. It is the major contributor to the pericallosal pial plexus (PP). CN, caudate nucleus; F, fornix; G, genu of corpus callosum. D, the medial surface of the right cerebral hemisphere. After partial removal of the cingulate gyrus (CG), the callosal sulcus is revealed. Forceps retract the A5 segment of the pericallosal artery. The posterior extension (arrow) of the A5 segment follows a corkscrew-like course within the callosal sulcus at the splenium (S) and forms the dense portion of the pericallosal pial plexus (PP). B, body of corpus callosum; CP, choroid plexus; F, fornix.

FIGURE 10. Lateral projection of a left vertebral artery angiogram showing the distal type of posterior pericallosal artery (black arrow), which runs to the splenium (S) and divides into two main branches. The superior branch (white arrowhead) courses within the callosal sulcus with a characteristic tortuosity and anastomoses with the posterior extension of the A5 segment. The inferior branch (black arrowhead) runs anteriorly and anastomoses with the branches of the medial posterior choroidal artery (white arrow) in the tela choroidea of the third ventricle.

In other instances where one or more of the A3 through A5 segments coursed in the cingulate sulcus and were, therefore, not involved with the corpus callosum, the prominent blood supply to the affected portions of the corpus callosum was provided by the median callosal artery, the long callosal artery, the opposite hemisphere's pericallosal artery, or any combination of these arteries. When the A5 segment coursed in the cingulate sulcus (35%), these arteries subsequently anastomosed with the posterior pericallosal artery in the splenial region (Fig. 5C).
The pericallosal artery was found to give rise to four types of branches that supply the corpus callosum: 1) the callosal artery, 2) the cingulocallosal artery, 3) the long callosal artery, and 4) the recurrent cingulocallosal artery. The callosal arteries, thin branches arising from the pericallosal artery, directly supplied the inclusium griseum and the superficial surface of the corpus callosum in the midline. They were present in 50% of the hemispheres and did not branch into the callosal sulcus. Their numbers varied between 0 and 3 (average, 0.7) per hemisphere, and their diameters ranged between 0.15 and 0.3 mm (average, 0.2 mm) (Figs. 5A and 11 and Table 2).

**TABLE 2. Characteristics of Branches from the Pericallosal Artery That Supply the Corpus Callosum**

<table>
<thead>
<tr>
<th>Arterial Branches</th>
<th>Diameter (mm)</th>
<th>Number</th>
<th>Occurrence (Hemispheres)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
<td>Average</td>
<td>Range</td>
</tr>
<tr>
<td>Callosal</td>
<td>0.15-0.3</td>
<td>0.2</td>
<td>0-3</td>
</tr>
<tr>
<td>Cingulocallosal</td>
<td>0.35-0.6</td>
<td>0.25</td>
<td>3-23</td>
</tr>
<tr>
<td>Long callosal</td>
<td>0.2-0.9</td>
<td>0.45</td>
<td>0-3</td>
</tr>
<tr>
<td>Recurrent cingulocallosal</td>
<td>0.2-0.5</td>
<td>0.25</td>
<td>0-7</td>
</tr>
</tbody>
</table>

The cingulocallosal artery played the most important role in the blood supply of the corpus callosum. It arose from the inferolateral aspect of the pericallosal artery and ran laterally into the callosal sulcus, where it divided into three arterial subgroups, one of which supplied the corpus callosum. The second, arranged in a brush-like formation, supplied the cingulate gyrus; the third followed the depths of the callosal sulcus and cours ed laterally to supply the radiation of the corpus callosum. The cingulocallosal arteries anastomosed with each other and with branches arising from the subcallosal, median callosal, and long callosal arteries to form the pericallosal pial plexus. This plexus was most developed in the region of the splenium, where it received a further contribution from the posterior pericallosal artery, a feature that was observed in all hemispheres. The cingulocallosal arteries ranged in number from 3 to 23 per hemisphere (average, 9). Their diameters ranged between 0.15 and 0.6 mm (average, 0.25 mm) (Figs. 5B, 6, and 11 and Table 2).

The long callosal artery, another branch arising from the pericallosal artery, coursed parallel with it in the callosal sulcus and had multiple branches that contributed to the pericallosal pial plexus. It was present in 55% of the hemispheres studied. The number ranged from 0 to 3 per hemisphere (average, 0.62), and the diameters ranged between 0.2 and 0.9 mm (average, 0.45 mm). The artery terminated in the body of the corpus callosum (24%) or in the medial longitudinal striæ at the splenium (16%). The remainder either anastomosed with the posterior pericallosal artery of the same hemisphere (48%) or crossed the midline and anastomosed with the posterior pericallosal artery of the opposite hemisphere (12%), both within the callosal sulcus in the splenial region (Figs. 5C, 6, and 11 and Table 2).

The recurrent cingulocallosal artery, a thin branch, arose from major cortical branches of the pericallosal artery: the superior internal parietal artery (40%), the paracentral artery (20%), the callosomarginal artery (16%), the anterior internal frontal artery (10%), the inferior internal frontal artery (10%), or the frontopolar artery (4%). It coursed on the medial surface of the cingulate gyrus toward the callosal sulcus, was present in 45% of the hemispheres, and contributed to the pericallosal pial plexus. The recurrent cingulocallosal arteries ranged in number
from 0 to 7 (average, 1.1) per hemisphere, and their diameters ranged between 0.2 and 0.5 mm (average, 0.25) (Fig. 11 and Table 2).

Posterior pericallosal artery

The posterior pericallosal artery (also known as the splenial artery) contributed to the blood supply of the corpus callosum, in particular the splenial portion, in all hemispheres. It arose from the main trunk of the parieto-occipital artery or its precuneal branch (52%), the P3 segment of the PCA (32%), the calcaine artery (7%), the temporo-occipital artery (7%), or the P2 segment of the PCA (2%). Three anatomic variations of the posterior pericallosal artery were identified: 1) proximal type (the origin of the artery was located a few millimeters inferior to the splenium and followed an S-shaped course toward the splenium [80%]); 2) distal type (the artery generally arose from a precuneal branch of the parieto-occipital artery and was located posterior to the splenium [10%]); and 3) double type (both proximal and distal arterial patterns were observed, and they anastomosed with each other within the callosal sulcus [10%]).

In all three variations, the posterior pericallosal artery divided into two main branches when it reached the splenium. The superior branch formed the main trunk and coursed within the callosal sulcus with a characteristic corkscrew-like tortuosity; it then anastomosed with the posterior extension of the A5 segment in 65% of the hemispheres. When the long callosal and/or the median callosal arteries were present, they were also occasionally involved with this anastomosis. In 35% of the hemispheres, the A5 segment coursed in the cingulate sulcus. In this instance, the median callosal and/or the long callosal arteries were dominant and anastomosed exclusively with the posterior pericallosal artery. All variations of these complex anastomoses formed the dense portion of the pericallosal pial plexus within the callosal sulcus in the splenial region. In 77.5% of the hemispheres, the inferior branch ran anteriorly and then gave rise to branches supplying the tail of the hippocampus, and/or the pulvinar of the thalamus, and/or the tela choroidea of the third ventricle. In the latter situation, it usually anastomosed with the medial posterior choroidal artery and occasionally reached as far as the foramen of Monro. In the remaining 22.5% of the hemispheres, the inferior branch was thin and short and supplied the fasciolar gyrus and the crus of the fornix. The posterior pericallosal artery ranged in number between 1 and 2 (average, 1.1) per hemisphere, and its diameter ranged between 0.4 and 1.0 mm (average, 0.7 mm) (Figs. 1, 7, A-C, 8, A and B, 9-11).

FIGURE 7. Anatomic variations of the posterior pericallosal artery. A, proximal type. In 80% of the hemispheres, the posterior pericallosal artery (arrowhead) arises from the PCA or one of its main branches, inferior to the splenium (S). B, distal type. In an additional 10% of hemispheres, the posterior pericallosal artery (arrowhead) generally arises from a precuneal branch of the parieto-occipital artery, posterior to the splenium. C, double type. In the remaining 10% of the hemispheres, both proximal and distal type arteries are present (arrowheads). In all instances, the posterior pericallosal artery courses toward the splenium, where it divides into two main branches, superior and inferior.
FIGURE 8. Medial surface of the right cerebral hemisphere. The posterior portion of the corpus callosum is shown. A, The proximal type of posterior pericallosal artery arises from the parieto-occipital artery (poa), runs to the splenium (S), and divides into two main branches. The superior branch (black arrow) courses within the callosal sulcus with a characteristic tortuosity. The inferior branch (white arrow) is thin and short and supplies the fascicolar gyrus and the crus of the fornix (F). The accessory posterior pericallosal artery (open arrow) arises from the precuneal branch of the parieto-occipital artery and runs to the callosal sulcus. B, body of corpus callosum; C, cuneus; ca, calcarine artery; CG, cingulate gyrus; M, midbrain; P, pulvinar of thalamus; PB, pineal body; PC, precuneus. B, after partial removal of the cingulate gyrus, the pericallosal pial plexus (PP) is revealed within the callosal sulcus. Forceps lift the posterior pericallosal artery to show more clearly the anatomy of its superior (black arrow) and inferior (white arrow) branches. The superior branch and the accessory posterior pericallosal artery (open arrow) anastomose with the posterior extension of the A5 segment and form the dense portion of the pericallosal pial plexus. C, cuneus; ca, calcarine artery; F, fornix; P, pulvinar of thalamus; PB, pineal body; poa, parieto-occipital artery; S, splenium.

In addition to the posterior pericallosal artery, a very fine artery that contributed to the blood supply of the splenium was observed in 25% of the hemispheres. It originated from the precuneal branch of the parieto-occipital artery, the hippocampal artery, the medial posterior choroidal artery, or the lateral posterior choroidal artery. Its diameter ranged from 0.2 to 0.4 mm (average, 0.3 mm). We have named this artery the "accessory posterior pericallosal artery" (Figs. 8, A and B, and 11).

FIGURE 9. Medial surface of the right cerebral hemisphere. The midbrain (M) has been cut. The posterior portion of the corpus callosum is shown. The distal type of posterior pericallosal artery arises from the precuneal branch of the parieto-occipital artery (poa) and runs to the splenium (S), where it divides into two main branches. The superior branch (white arrow) courses within the callosal sulcus. The inferior branch (black arrow) runs anteriorly then gives rise to branches to the tela choroidea of the third ventricle (TV). F, fornix; LG, lingual gyrus; LV, lateral ventricle; PB, pineal body; poa, parieto-occipital artery; S, splenium.
DISCUSSION

The fibers of the corpus callosum are the major connecting pathways between the cerebral hemispheres of the human brain (4, 30). Various neurological diseases involve the corpus callosum. For instance, gliomas can arise at this site, and adjacent falcine meningiomas can cause compression. In addition, vascular malformations and aneurysms can occur in the region of the corpus callosum. An incision into the corpus callosum is generally required to reach the lateral or third ventricles. However, a callosal incision can result in various disorders: disruption of interhemispheric transfer of information, interference with visuospatial transfer, difficulty in learning bimanual motor tasks, memory problems, and other deficits, including alexia, apraxia, and astereognosis (1, 6, 21, 25, 28, 33-35).

Previous studies have dealt with only limited aspects of the anatomic features of the blood supply to the corpus callosum (2, 3, 5, 9-11, 13-16, 18-20, 22, 23, 25-29, 32-36), and very few articles have addressed the vascularity of this region as one anatomic entity (12, 17, 24, 31). It has been the aim of the present investigation to examine the blood supply of the corpus callosum, to provide adequate information to the neurosurgeon. This accumulation of knowledge can be applied to the recognition of anatomic landmarks and variations in arterial patterns during surgery, which can ultimately guide the exploration to a successful outcome.

The following summarizes our findings regarding the microsurgical anatomic features of the blood supply to the corpus callosum and indicates their surgical relevance. Three main arterial systems supply the corpus callosum: the ACoA, the pericallosal artery, and the posterior pericallosal artery.

Contribution of the ACoA

The ACoA branches are divided into three subgroups: the hypothalamic artery, the subcallosal artery, and the median callosal artery. The hypothalamic artery arose from the ACoA in 85% of our specimens; in the other 15%, it arose from the subcallosal artery or the median callosal artery. In no specimen did the hypothalamic artery contribute to the blood supply of the corpus callosum.

The subcallosal artery is rarely mentioned in the literature, because of the use of a different classification for the various branches arising from the ACoA complex (19, 34). Marinkovic et al. (19) found a subcallosal artery present in 91% of his specimens, whereas it occurred in 50% of our specimens, always as a single dominant artery.

Previous studies have discussed the contribution of the median callosal artery to the blood supply of the corpus callosum, and the artery was reported to be present in less than 20% of specimens (2, 11, 14, 16, 19, 23, 27, 29, 31, 34). In our observations, the median callosal artery was present in 30% of the specimens. We identified two vascular patterns, which are based on their distal arterial distributions, and we called these “classical” and “hemispheric.” The presence of the median callosal artery and the existence of anastomoses with the various branches of the PCA, middle cerebral artery, or ACA systems can provide an adequate source of collateral flow when temporary vessel occlusion is needed during surgery.

In an earlier publication (34) by the senior author (M.G.Y.), the branches of the ACoA complex were classified using different terminology. The previous terminology has been modified in this study as follows: the small third A2 is now identified as the subcallosal artery, the moderate third A2 as the classical type of median callosal artery, and the large third A2 as the hemispheric type of median callosal artery.

Marinkovic et al. (19) classified the branches of the ACoA according to the diameter at their origin as either small (hypothalamic) or large (subcallosal and median callosal). We have advocated classifying these arteries according to their territories of supply, because occasionally, in different specimens, the diameter of the hypothalamic artery or the subcallosal artery was found to be equal to, or larger than, that of the median callosal artery. Thus, when we explore the ACoA complex during surgery, we cannot conclusively identify its branches simply by comparing the diameters at their origins.

In our study of 20 brain specimens, we did not observe the azygos variation of the ACA. However, in the literature, the incidence is reported to range from 1 to 5% (2, 11, 13, 15, 34).

Before surgically approaching the ACoA complex in the case of an aneurysm, arteriovenous malformation, or tumor, the possible arterial variations that may occur in this area must be carefully considered. In particular, a careful study of the angiogram is strongly indicated because of the very high probability of the presence of a subcallosal artery or a median callosal artery, and because preserving these important vessels during surgery is crucial to a successful outcome.

Contribution of the pericallosal artery
The anatomic course of the pericallosal artery shows some variations. In 60% of the hemispheres in our study, the A3 through A5 segments all coursed in the callosal sulcus; in a further 32.5%, at least one segment coursed in the cingulate sulcus. In the remaining 7.5%, the A3 through A5 segments all coursed in the cingulate sulcus and were never involved with the corpus callosum. Therefore, when performing an interhemispheric approach, one must take into consideration that the pericallosal artery may be located in the cingulate sulcus rather than the callosal sulcus. For this reason, care should be taken to ensure that the ipsilateral cingulate gyrus is not confused with the white corpus callosum.

Perlmutter and Rhoton (24) were the first to classify the branches of the pericallosal artery that supply the corpus callosum as the “short callosal artery” and the “long callosal artery.” They noted (24) that the short callosal arteries, which were found in 98% of the hemispheres, averaged seven per hemisphere and penetrated directly into the corpus callosum, rendering them the major arterial supply. In our study, four types of pericallosal artery branches to the corpus callosum were identified: the callosal, the cingulocallosal, the long callosal, and the recurrent cingulocallosal arteries. The short callosal arteries described by Perlmutter and Rhoton are anatomically consistent with the arteries that we describe here as “callosal” and “cingulocallosal.” We prefer this differentiating nomenclature, because we agree with Malobabic et al. (17) and Wolfram-Gabel et al. (31) that the cingulocallosal artery does not penetrate the corpus callosum directly but instead provides the main supply to the pericallosal pial plexus within the callosal sulcus, which is the leading source of blood supply to the corpus callosum, and also contributes to the cingulate gyrus. The cingulocallosal artery was present in all of the hemispheres we studied.

The callosal artery, on the other hand, directly supplied the superficial surface of the corpus callosum along the midline, without giving rise to any branches leading to the depths of the callosal sulcus. Those thin callosal arteries were present in 50% of the hemispheres.

The long callosal artery, which arose from and ran parallel to the pericallosal artery in the callosal sulcus, was found in 55% of the hemispheres in our study. Perlmutter and Rhoton (24) found this artery in only a few cases in their study. The branches of the long callosal artery contributed to the formation of the pericallosal pial plexus. Thus, it participated in providing blood supply to the corpus callosum, the radiation of the corpus callosum, and the cingulate gyrus. In addition, it was usually a good source for the anastomosis with the posterior pericallosal artery.

The recurrent cingulocallosal artery was a thin branch that arose from the major cortical branches of the pericallosal artery and contributed to the pericallosal pial plexus. It was present in 45% of the hemispheres we studied.

Contribution of the posterior pericallosal artery

Several studies have reported that the posterior pericallosal artery contributes to the blood supply of the corpus callosum and anastomoses with the pericallosal artery at the splenium (10, 12, 17, 18, 22, 28, 30-36). Yamamoto and Kageyama (32) found the posterior pericallosal artery to be present in 62.8% of the hemispheres studied, and Margolis et al. (18) reported it in 35% of the hemispheres in their study. Milisavljevic et al. (22) found anastomosis between the pericallosal artery and the posterior pericallosal artery at the splenium in 75.7% of the hemispheres. The anastomosis of posterior pericallosal artery with the pericallosal artery at the splenium was present in all of the specimens (100%) we studied, which is consistent with the findings reported by Zeal and Rhoton (36).

Our observations revealed three different anatomic patterns of the posterior pericallosal artery. In 80% of the hemispheres, the artery arose from either the PCA or one of its main branches, a few millimeters inferior to the splenium, and followed an S-shaped course toward the splenium; we called this pattern the “proximal type.” In 10% of the hemispheres, the posterior pericallosal artery generally arose from the precuneal branch of the parieto-occipital artery and was located posterior to the splenium; we termed this the “distal type.” In the remaining 10% of the hemispheres, the posterior pericallosal artery distribution arose from both posterior and inferior locations; hence, we identified this as the “double type.” In all instances, the artery coursed toward the splenium, where it divided into two main branches, superior and inferior. The superior branch formed the main trunk, ran within the callosal sulcus with a characteristic corkscrew-like tortuosity, and anastomosed with the posterior extension of the A5 segment, the long callosal artery, the median callosal artery, or two or three of these arteries. Therefore, they formed the dense portion of the pericallosal pial plexus. The inferior branch coursed beneath the splenium and then continued anteriorly to supply the fasciolar gyrus, the fornix, the tela choroidea of the third ventricle, the tail of the hippocampus, the pulvinar of the thalamus, or any combination of these.

A very fine artery arising from one of the branches of the PCA and contributing to the blood supply of the splenium was a further finding resulting from our study. It was present in 25% of the hemispheres and was named the “accessory posterior pericallosal artery.”

It is worthy of mention that all of the variations in the main arterial systems of the corpus callosum can be investigated preoperatively using modern neuroradiological studies, including magnetic resonance imaging, magnetic resonance angiography, and cerebral angiography. Applying the knowledge of the anatomy of these variations to the neuroradiological studies allows the individual vascular patterns and collateral
Our study of the arteries of the corpus callosum resulted in the identification of certain elements that broaden our knowledge and that can be applied to the process of defining a precise concept and strategy for the surgical approach to this region. It offers an improved capacity to recognize significant anatomic landmarks during surgery, which enables the neurosurgeon to proceed on an accurate course when exploring this complex region.

ACKNOWLEDGMENTS

We thank B. Lee Ligon, Ph.D., and Dianne C.H. Yasargil, R.N., for editing the text, Peter Roth and Ron M. Tribell for providing original artwork, and Professor Stephan Kubik and Rosemarie Frick for assistance. We are grateful to Professor Ossama Al-Mefty for support and guidance during the completion of this study in the Microsurgical Anatomy Laboratory of the Department of Neurosurgery at the University of Arkansas for Medical Sciences.

REFERENCES


The authors have completed an excellent study of the arteries of the corpus callosum, which is further enhanced by the illustrations. The anatomy described here will be useful in operative approaches directed along the whole medial surface of the hemisphere from the subfrontal area all the way back to the occipital region. The authors have provided an especially clear description of the perforating arteries arising from the anterior communicating artery (ACoA). These studies document that it is best to direct transcallosal approaches between the pericallosal arteries rather than on the lateral side of the arteries, which will lead to interruption of branches of the callosal arteries.

Albert L. Rhoton, Jr.
Gainesville, Florida

The authors dissect 20 brains with injected arteries and study and measure the larger and smaller arteries to the corpus callosum and surrounding structures. Many of the measurements and descriptions have also been described in different articles from our Institute. I compare the results of both study groups and give some examples.

In the material of Türe et al., the distance measured between the ACoA and the lamina terminalis is 4 mm (range, 1-9 mm); in our material it is 4.9 mm (range, 0-10 mm). Türe et al. found 2.5 (range, 1-6) perforating branches of the ACoA; we found 3 (range, 0-10). The diameters were measured by Türe et al., together with arteries to the corpus callosum; in our material, the measurements were taken only to the...
The diencephalon. For this group, the two arteries have nearly the same diameters. The subcallosal artery is newly described and was found in 50% of the specimens, and the median callosal artery was found in 30% of the specimens. Türe et al. identified both arteries much more often than did other researchers. The course of the ascending (subcallosal) segment of the pericallosal artery was described in both cases as S shaped, similar to the description given by Lang and Häckel. The width of this segment was approximately 2.5 mm. The course of the pericallosal arteries in the A3 to the A5 segment was seen in the callosal sulcus in 60% of the specimens. They described also that the artery runs at least partly into the cingulate sulcus in 32.5% of the specimens, and in approximately 10%, the midline crosses and runs into the opposite hemisphere. (This has also been seen in dissections by other researchers.)

A good description is given of the posterior pericallosal artery and the branches of the pericallosal artery to the corpus callosum. In our study, this small branch has a width of 0.36 mm (range, 0.2-0.8 mm). Its origin was found to be the parieto-occipital artery in approximately 41% of our specimens and in 52% of Türe et al.'s specimens; it originated from the medial-occipital artery in approximately 37% of our specimens and from the P3 segment. In Türe et al.'s study, it originated from the calcarine artery in 7% and in our study in 10.3% of specimens. We also found the origin from the lateral occipital artery, from the anterior cerebral artery, from the posterior medial choroidal branch, and from the inferior temporal branch. We described anastomoses and some other variations. A very subtle microanatomy is described by Türe et al., the course and the branches of this small artery, which can be important during supra- or infratentorial approaches to the area of the splenium of the corpus callosum. The photographs of the work are excellent, the drawings easy to understand.

Johannes Lang

Würzburg, Germany

Key words: Corpus callosum; Median callosal artery; Microsurgical anatomy; Pericallosal artery; Pericallosal pial plexus; Posterior pericallosal artery; Subcallosal artery

Accession Number: 00006123-199612000-00001

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Version: rel10.2.0, SourceID 1.11354.1.65
Arteries of the insula

UĞUR TÜRE, M.D., M. GAZİ YAŞARGİL, M.D., OSSAMA AL-MEFTİ, M.D., AND DIANNE C. H. YAŞARGİL, R.N.

Department of Neurosurgery, University of Arkansas for Medical Sciences, Little Rock, Arkansas

Object. The insula is located at the base of the sylvian fissure and is a potential site for pathological processes such as tumors and vascular malformations. Knowledge of insular anatomy and vascularization is essential to perform accurate microsurgical procedures in this region.

Methods. Arterial vascularization of the insula was studied in 20 human cadaver brains (40 hemispheres). The cerebral arteries were perfused with red latex to enhance their visibility, and they were dissected with the aid of an operating microscope.

Arteries supplying the insula numbered an average of 96 (range 77–112). Their mean diameter measured 0.23 mm (range 0.1–0.8 mm), and the origin of each artery could be traced to the middle cerebral artery (MCA), predominantly the M₁ segment. In 22 hemispheres (55%), one to six insular arteries arose from the M₁ segment of the MCA and supplied the region of the limen insulae. In an additional 10 hemispheres (25%), one or two insular arteries arose from the M₂ segment of the MCA and supplied the region of either the superior or inferior perinsular sulcus. The insular arteries primarily supply the insular cortex, extreme capsule, and, occasionally, the claustrum and external capsule, but not the putamen, globus pallidus, or internal capsule, which are vascularized by the lateral lenticulostriate arteries (LLAs). However, an average of 9.9 (range four–14) insular arteries in each hemisphere, mostly in the posterior insular region, were similar to perforating arteries and some of these supplied the corona radiata. Larger, more prominent insular arteries (insulaopercular arteries) were also observed (an average of 3.5 per hemisphere, range one–seven). These coursed across the surface of the insula and then looped laterally, extending branches to the medial surfaces of the opercula.

Conclusions. Complete comprehension of the intricate vascularization patterns associated with the insula, as well as proficiency in insular anatomy, are prerequisites to accomplishing appropriate surgical planning and, ultimately, to completing successful exploration and removal of pathological lesions in this region.

KEY WORDS • insula • sylvian fissure • lateral lenticulostriate artery • middle cerebral artery • limbic system • paralimbic system • microsurgical anatomy

Arteries of the Insula

The insula, or island of Reil, forms the base of the sylvian fissure and constitutes the invaginated portion of the cerebral cortex that covers the claustrum and the basal ganglia. Adequate visualization of the insula requires that the sylvian fissure be opened along its entire length. The insula is one of the paralimbic structures known as the mesocortex, which is anatomically and functionally interposed between the allocortex and neocortex. The insula has long been a subject of research and speculation; however, the distinct realm of its function continues to elude us. It has been described as a visceral sensory area, visceral motor area, supplementary motor area, vestibular area, and an area related to certain aspects of speech and/or language. Broad concepts outlining certain features related to the insula are available, but firm definitions identifying its anatomical connections and established conclusions concerning its functions remain to be investigated. The insula can be the site of pathological processes such as neuroepithelial and meningeal tumors and vascular malformations; hence, knowledge of the anatomy and vascularization of the insula is essential for performing meticulous surgery in this region.

Anatomy of the Insula

A detailed topographic anatomy of the insula was described in a previous article by the authors and, therefore, only a brief outline will be documented here. The insula has a triangular pyramidal shape and is separated from the opercula by the anterior, superior, and inferior perinsular sulci. The superior perinsular sulcus is located beneath the frontoparietal operculum, the inferior perinsular sulcus beneath the temporal operculum, and the anterior perinsular sulcus beneath the orbitofrontal operculum. The limen insulae is the entranceway into the insula and forms the lateral limit of the sylvian vallecula (or anterior perforated substance). The central insular sulcus traverses the insula from the superior perinsular sulcus to the limen insulae and divides it into anterior and posterior portions. The anterior insula is composed of the anterior,
Arteries of the insula

middle, and posterior short insular gyri, as well as the accessory and transverse gyri at its anteroinferior region. The gyri of the anterior insula fuse to form the insular apex, which is its most superficial area. The posterior insula consists of the anterior and posterior long insular gyri, which are separated by the postcentral insular sulcus. The insula constitutes the cortical covering that lies over the claustrum and putamen of the lentiform nucleus.

Segments of the MCA

The MCA is the most complex of all cerebral vessels (Fig. 1). This artery is divided into five major segments: M1 through M5. The M1 (sphenoidal) segment extends from the bifurcation of the ICA to the main MCA bifurcation, which is located adjacent to the limen insulae. The M1 (insular) segments extend from the main bifurcation to the perinsular sulci and the M1 (opercular) segments extend from the perinsular sulci to the lateral surface of the brain in the Sylvian fissure. The M1 (parainsular) segments are located on the parasympathetic surface of the brain and the M1 (terminal) segments constitute distal extensions of the M1 segments.\[^{5,7,9,16,18,19,21,22,25,34,35,38}\]

Materials and Methods

The microsurgical anatomy of the arteries of the insula was studied in 20 formalin-fixed human cadaver brains (40 hemispheres). The ICA and vertebral arteries were dissected and cannulated at the neck, after which they were perfused with red latex to enhance their visibility. Following removal of the calvaria, the dura was opened carefully, the arachnoid and pia were separated, and the sylvian fissure was opened. The origin, caliber, number, and course of the LLAs were studied with the aid of the operating microscope by using ×6 to ×40 magnification. The cortical branches of the MCA could thus be demonstrated and their territories analyzed. Removal of the orbitofrontal, frontoparietal, and temporal opercula revealed the M1, M2, and M3 segments of the MCA. Particular care was taken to preserve the pia that lay over the insular surface during removal of the opercula. The arteries of the insula were studied, placing particular emphasis on locating their origin and determining their number, diameter, and territory. In two specimens, coronal sections were explored to investigate the subcortical territory of the insular arteries. In three specimens, using the fiber-dissection technique, we defined the white matter pathways and dissected them in a stepwise fashion, promoting a precise study of the LLA territories in the putamen, globus pallidus, anterior commissure, and internal capsule.

Results

Sphenoidal (M1) Segment of the MCA

In all specimens the ICA bifurcated into the MCA and ACA at the central portion of the anterior perforated substance. The M1 segment of the MCA courses laterally and superiorly within the sylvian vallecula in the depths of the Sylvian fissure and around the limen insulae to the insular apex, where it formed a genu. The average angle of the genu measured 97° (range 90–130°). The average distance of the genu from the limen insulae measured 4.8 mm (range 2.9–9 mm). The average diameter of M1 segment was 3.21 mm (range 2.6–4 mm) and the average length was 23.4 mm (range 15–38 mm). The course of the M1 segment within the Sylvian vallecula was found to be anteroseptal, superior, or posterosuperior. The demarcation distinguishing the M1 from the M2 segment is the bifurcation of the MCA, which is located at the genu of the MCA, adjacent to the limen insulae (Fig. 2). We designated this particular bifurcation of the MCA as the main bifurcation. In 23 hemispheres (57.5%), the main bifurcation was located at the genu. In an additional 11 hemispheres (27.5%), the main bifurcation was located 4 to 10 mm distal to the genu and, in the remaining six hemispheres (15%), it was located 5 to 8 mm proximal to the genu. In two (5%) of the 40 hemispheres, the temporal branch of the M1 segment was strong and in one other hemisphere (2.5%) the frontal branch was strong, distinctly resembling the main bifurcation of the MCA; thus it was named a “false bifurcation.”\[^{34,35}\]

Variations of the M1 segment and the main bifurcation site of the MCA are described in detail in previous publications by the senior author (M.G.Y.\[^{34,35}\]).

The anatomical patterns followed by branches of the M1 segment were observed to vary. They can be divided into three groups according to their territory of supply, the cortical arteries, and the LLAs.

Cortical Arteries. In 38 hemispheres (95%) the M1 segment gave rise to one to three major cortical branches, which were mainly located on the lateral aspect of M1 segment (75.8%), supplying the temporal lobe, or on the medial and inferior aspect of the segment (24.2%), supplying the frontal lobe. In seven hemispheres (17.5%), we found one and, occasionally, two small arteries (uncal arteries) 0.3 to 0.5 mm in diameter, supplying the piriform cortex. We did not designate this as a major cortical artery. The variations followed by the major cortical branches of the M1 segment were classified into four types (Fig. 3). In Type A the M1 segment gives rise to a temporal (lateral) branch. This was observed in 23 hemispheres (57.5%); in 17 hemispheres (42.5%), there was one temporal branch; in five hemispheres (12.5%), there were two temporal branches; and in one hemisphere (2.5%) there were three temporal branches. In Type B the M1 segment gives rise to temporal (lateral) and frontal (medial) branches. This was observed in 14 hemispheres (35%); in 11 hemispheres (27.5%), there was one temporal and one frontal branch and, in three hemispheres (7.5%), there were two temporal and one frontal branch. In Type C the M1 segment gives rise to a frontal branch only and no temporal branch. This was observed in one hemisphere (2.5%). In Type D the M1 segment gives rise to no major cortical branches apart from the LLAs and uncinate arteries. This was observed in two hemispheres (5%).

Lateral Lenticulostriate Arteries. In all hemispheres the M1 segment gave rise to the LLAs, located mainly on the inferomedial aspect of the M1 segment within the Sylvian vallecula. These arteries penetrated to the central and lateral portions of the anterior perforated substance, playing an important role in the blood supply of the substantia innominata, putamen, globus pallidus, head and body of the caudate nucleus, internal capsule and adjacent corona radiata, and the lateral portion of the anterior commissure. The LLAs numbered between one and 15 (average 7.75) per hemisphere, and no clear correlation appeared to exist between the length of the M1 segment and the number of LLAs. The diameters of the LLAs at their origin ranged between 0.1 and 1.5 mm (average 0.45 mm). The majority (73%) of LLAs measured less than 0.5 mm in diameter. The remainder (27%) were larger in diameter and most
Fig. 1. Photographs of brain specimens. **Upper Left**: The lateral surface of the left hemisphere is supplied by the M₄ and M₅ segments of the MCA. **Upper Right**: The same specimen is shown following removal of the entire opercula with preservation of all segments of the MCA. **Lower**: The same specimen. The M₃, M₄, and M₅ segments of the MCA have been removed, and the M₆ segment, which supplies the insula, has been preserved over the insular cortex. White letters denote sulci and fissures. 1 = lateral orbitofrontal artery; 2 = prefrontal artery; 3 = precentral artery; 4 = central artery; 5 = anterior parietal artery; 6 = posterior parietal artery; 7 = angular artery; 8 = temporoparietal cortex; 9 = posterior temporal artery; 10 = middle temporal artery; 11 = anterior temporal artery; 12 = temporal polar artery; ang = angular gyrus; ar = ascending ramus of sylvian fissure; cs = central sulcus of Rolando; F₁ = superior frontal gyrus; F₂ = middle frontal gyrus; F₃ = inferior frontal gyrus; f₁ = superior frontal sulcus; f₂ = inferior frontal sulcus; hr = horizontal ramus of sylvian fissure; it = inferior trunk of M₁ segment; op = pars opercularis of F₃; or = pars orbitalis of F₃; pcg = precentral gyrus; pcs = precentral sulcus; pg = postcentral gyrus; ps = postcentral sulcus; smg = supramarginal gyrus; st = superior trunk of M₂ segment; T₁ = superior temporal gyrus; T₂ = middle temporal gyrus; T₃ = inferior temporal gyrus; t₁ = superior temporal sulcus; t₂ = inferior temporal sulcus; tdl = terminal ascending limb of sylvian fissure; tb = temporal branch of the MCA; tdl = terminal descending limb of sylvian fissure; tr = pars triangularis of F₃; tts = transverse temporal sulcus.
Arteries of the insula

divided into many smaller branches. We observed at least one large, maximum four, LLAs in each hemisphere. The origins of the LLAs varied. Seventy-eight percent originated from the M1 segment, usually on the inferomedial aspect. In 18%, however, the LLAs originated from a frontal or temporal branch and, in 4%, the LLAs originated from the superior or inferior trunk of the M1 segment and were located near to the main bifurcation of the MCA. There were no communications among the branches of LLAs in the subarachnoid space. In 15 hemispheres (37.5%), the M2 segment gave rise to a frontal branch (lateral orbitofrontal artery) and, in nine hemispheres (22.5%), this frontal branch gave rise to strong LLAs (Fig. 2 lower). In the remaining six hemispheres (15%), the LLAs arose directly from the M1 segment, in proximity to the origin of the frontal branch. Following their branching from the M1 segment, the LLAs turned abruptly, forming an acute angle at their origins, and coursed medially 4 to 5 mm, before turning superiorly to enter the lateral portion of the anterior perforated substance. Viewed laterally, the LLAs revealed a fanlike pattern, beginning at the base of the brain and radiating to extend over almost the entire internal capsule (Fig. 4).

In 22 hemispheres (55%), the small branches of the M1 segment were observed to contribute to the vascularization of the insula. Between one and six arteries arose from the distal M1 segment and supplied the region of the limen insulae. In 25 hemispheres (62.5%), the lateral orbitofrontal artery arose from the M1 segment, extending branches to supply the transverse and accessory insular gyri; this artery became the M2 segment and the M1 segment was absent. Similarly, when the temporal polar and anterior temporal arteries arose from the temporal branch of the M1 segment on its lateral aspect, the M1 segment of these arteries was also absent and no branches supplied the insula.

Insular (M2) Segment of the MCA

The MCA was observed to divide into superior and inferior trunks, usually at the level of the limen insulae, and the trunks coursed over the insular cortex as the M1 segment. In 35% of hemispheres, the superior trunk was larger than the inferior trunk; in an additional 15% of hemispheres they were equal; and in the remaining 50% of hemispheres, the inferior trunk was larger. The average diameter of the superior trunk of the M1 segment was 2.51 mm (range 1.6–3 mm) and the average diameter of the inferior trunk of the M1 segment was 2.35 mm (range 1.3–3 mm). The angle between the superior and inferior trunks of the M1 segment was found to vary; the average was 91º (range 35–160º). In three hemispheres (7.5%), either the superior or inferior trunk of the M1 segment gave rise to one or two small LLAs, immediately after the bifurcation.

In 22 hemispheres (55%) either the superior or inferior trunk of the M1 segment (whichever trunk was more dominant) bifurcated again distal to the main bifurcation, giving rise to an “intermediate trunk.” In 18 hemispheres (45%), this intermediate trunk arose from the superior trunk and, in the remaining four hemispheres (10%), it arose from the inferior trunk. In five hemispheres (12.5%), this second bifurcation (intermediate trunk) occurred close to the main bifurcation, giving the impression of a trifurcation. In an additional hemisphere (2.5%), both the superior and inferior trunks bifurcated immediately after the main bifurcation, resembling a quadrifurcation.

At the region of the limen insulae, not always are just the superior and inferior trunks of the MCA encountered: sometimes three to five truncal arterial branches are encountered as well. Along the superior and inferior perinsular sulci, the M1 segment had an average of 9.6 branches (range eight–12 branches), before becoming M2 segment. These branches arose mainly from the superior trunk and branched further over the anterior insula.

In each hemisphere, the prefrontal artery was located in the region of the anterior insular point (Figs. 1, 4 upper, and 5). The prefrontal, precentral, and central arteries, and, in 22.5% of the hemispheres, the anterior and posterior parietal arteries fanned out over the insula from the superior trunk. They predominantly supplied the anterior portion of the insula. On reaching the superior perinsular sulcus the branches angled sharply to become the M2 segment, the so-called “candelabra arteries.” In each hemisphere the central artery, or the trunk that included the central artery, traveled either partially or totally along the central sulcus of the insula (Figs. 1, 4 upper, and 6). It was never observed to originate from the frontal or temporal branches that arose from the M1 segment. The central insular sulcus is the most vascularized portion of the insula. At the region of the posterior insular point, one or two arteries were observed to course to the postinsular sulcus to become the M3 segment and, later to divide to become the M4 segment on the surface of the cerebral cortex at the posterior aspect of the sylvian fissure. These arterial branches represent the continuation of the MCA along the sylvian fissure and, subsequently, over the posterior portion of the insula, providing multiple insular arteries. The posterior parietal artery was always observed to arise from these branches (Figs. 1 and 4 upper). The central artery was observed to arise from these branches in three hemispheres and from the anterior parietal, posterior parietal, angular, and temporopolar sulci in four additional hemispheres. The posterior and middle temporal arteries arose from the inferior trunk of the M1 segment and coursed along the region of the inferior perinsular sulcus to become the M1 segment. The temporal branch, which arises from M1, always courses laterally to other M1 segments, which are located over the surface of the insula.

Opercular (M3) Segment of the MCA

The course of the M2 segment’s complex of arteries commences in the anterior, superior, and inferior perinsular sulci, continues along the hidden medial surface of the opercula, and becomes the course of the M3 segments on the surface of the sylvian fissure (Fig. 5). The M3 segments pass over the insula parallel to the M1 segment, but extend in opposite directions. The M3 segments supplied the medial surface of the opercula; however, in 10 hemispheres (25%), they also gave rise to one or two small insular arteries, which supplied the region of either the superior or inferior perinsular sulcus. The lateral orbitofrontal and temporal polar arteries demonstrated a particular characteristic: when these arteries arose from the M3 segment, they immediately became the M4 segments, giving no branches to the insula.
Fig. 2. Photographs of brain specimens. Upper: Inferior view is shown of left MCA in the region of the anterior perforated substance following removal of the temporal lobe. The M1 segment is retracted with forceps to expose the LLAs (lla). Lower: The temporal branch of the M1 (tb) is raised to rotate the M1 segment and expose the frontal branch of the MCA (fb). The arrow indicates an LLA arising from the frontal branch (lateral orbitofrontal artery). The asterisk indicates the main bifurcation of the MCA. I = olfactory nerve; III = oculomotor nerve; A1 = precommunicating segment of ACA; ach = anterior choroidal artery; li = limen insulae; M1 = sphenoidal segment of the MCA; on = optic nerve; ot = optic tract; P2 = ambient segment of posterior cerebral artery; pco = posterior communicating artery. See previous figure legend for additional abbreviations.
Arteries of the insula

Parasylvian (M1) and Terminal (M4) Segments of the MCA

The M1 segments course laterally to exit the sylvian fissure and become M2 segments on the lateral surface of the hemisphere. The M1 and M2 segments consist of 12 main arteries, which have been documented and named in earlier publications according to their territories of supply. They include lateral orbitofrontal, prefrontal, precentral, central, anterior parietal, posterior parietal, angular, temporopolar, posterior temporal, middle temporal, anterior temporal, and temporal polar arteries (Fig. 1). No branches from the M2 and M1 segments were observed to supply the insula.

Arteries Supplying the Insula

The insula receives its blood supply predominantly from the M1 segment. An examination of 40 hemispheres revealed 75 to 104 insular arteries originating from this segment. However, in 22 hemispheres (55%), between one and six insular arteries arose from the distal M1 segment and supplied the region of the limen insulae. In 10 hemispheres (25%), one or two insular arteries arose from the M2 segment and supplied the region of either the superior or inferior perinsular sulcus. We observed no branches to the insula from the M1 and M2 segments. In each hemisphere, an average of 96 insular arteries (range 77–112 insular arteries) were found supplying the insula (Figs. 4 upper, 6, and 7). The average diameter of these arteries was 0.23 mm (range 0.1–0.8 mm). An average of 9.9 insular arteries (range four–14 insular arteries) in each hemisphere resembled perforator arteries, and their distribution occasionally reached as far as the corona radiata (Figs. 7 and 8). We sometimes observed a larger caliber insular artery that coursed along the surface of the insula and then looped laterally, providing branches to both the insula and the medial surface of the operculum. We named this artery the “insuloopercular artery” (Fig. 4 upper). Approximately 85 to 90% of insular arteries were short and supplied the insular cortex and extreme capsule; 10% were medium sized and also supplied the claustrum and external capsule; and the remaining 3 to 5% were long and extended as far as the corona radiata (Fig. 8). The long insular arteries were perforator-like and mostly located in the posterior region of the insula. The putamen, globus pallidus, and internal capsule were vascularized by the LLAs (Fig. 4 lower). The external capsule was found to be the border of territories supplied by the LLAs and the insular arteries. We observed no gross communications between the insular arteries and LLAs.

Discussion

The MCA is the most complex of the cerebral vessels. This artery supplies almost the entire lateral surface of the hemisphere, as well as the insula, the lentiform nucleus, and the internal capsule. Microsurgical anatomy of the MCA, especially that of the M1 segment and the LLAs, has been examined and analyzed in detail in many studies. It is well known that chronic hypertension induces pathological changes in cerebral vessels, resulting in either their occlusion or rupture, which leads to lacunar infarctions or intracerebral hemorrhages, respectively. The most common site of a spontaneous intracerebral hemorrhage is the lenticular region, observed in 35 to 50% of patients. Because lenticular structures are located within the territory of the LLAs and Heubner’s artery, when hemorrhage is suspected to have occurred from these vessels, the importance of being familiar with the anatomy of the LLAs is clearly of great relevance. Marinovic and colleagues observed between three and 18 LLAs (average nine LLAs). They explored and described every single origin of the LLAs and found no communications among these vessels in either their extracerebral or intracerebral segments. Duret has claimed that the LLAs course laterally as far as the putamen. He has asserted, moreover, that the more lateral structures, such as the claustrum and external capsule, derive their blood supply from vessels penetrating the insula. Beevor has concurred with Duret, confirming this lateral boundary of the LLAs. Both have stated that no communications exist among the lateral LLAs and the insular arteries. Shellshear injected a coloring agent into the MCA after ligating the M1 segment. He discovered injection material in the striatum, claustrum, and external capsule, whereas the insular cortex was clear. Our study confirmed that the external capsule is the margin of territories supplied by the LLAs and the insular arteries. We found no gross evidence of communications between these two arterial systems. Insular arteries can be coagulated to devascularize intrinsic tumors and vascular malformations in the insular region, without damaging the vascularization of the putamen and internal capsule. However, long insular arteries should be preserved because of possible infarction in the corona radiata (Fig. 8). Some striate AVMs have been observed to receive their blood supply from these two groups of arteries, which indicates the potential existence of microcommunications between the LLAs and the insular arteries (Fig. 9).
FIG. 4. Photographs of brain specimens. Upper: The insula is shown following removal of the frontal, parietal, occipital, and temporal lobes from the perinsular sulci. The arteries of the insula originate from the M1 segment. The insulo-opercular arteries (arrow) supply the insula and operculum. Lower: Fiber dissection of this area reveals vascularization of the lentiform nuclei (which have been removed) and vascularization of the internal capsule by the LLAs (arrow), which arise from M1 segment. ac = anterior commissure; alg = anterior long insular gyrus; asg = anterior short insular gyrus; cis = central insular sulcus; ia = insular apex; ic = internal capsule; it = inferior trunk of M1; msg = middle short insular gyrus; P2 = ambient segment of the posterior cerebral artery; plg = posterior long insular gyrus; psg = posterior short insular gyrus. See previous figure legends for additional abbreviations.
Arteries of the insula

The frontal branch, which originates from the M1 segment, is of surgical significance. In two hemispheres (5%), the LLAs arose from the frontal branch of the M1 segment (Fig. 2 lower). An aneurysm located in this region of the M1 segment can be mistakenly diagnosed as an MCA bifurcation aneurysm. During surgery, a clip applied to the aneurysm can occlude those LLAs that arise from the frontal branch, often close to the origin of the frontal branch at the M1 segment. This maneuver can result in postoperative hemiplegia in the patient. It is important to be aware that LLA can also arise in proximity to the MCA bifurcation and, occasionally, from the superior or inferior trunk of M1. The exact location and relationship of these vessels to the aneurysm is an important consideration to take into account both before and during surgery. The configuration of the LLAs and related arteries can be determined on detailed angiography, and their location can be verified at surgical exploration.

Umansky, et al. have described the detailed anatomy of proximal segments of the MCA. Their study confirms that microvascular reconstructive surgeries, such as anastomosis, grafting, and reimplantation of arterial branches, are viable procedures in the insular area. They observed that the M2 segment could be raised 3 to 5 mm without stretching the pial vessels supplying the insula. They also noted that the M2 segment offers potential for performing a microvascular anastomosis. It is important, however, to be fully aware which cortical branch of the M1 segment originates from which trunk of the M1 segment. It is especially relevant to investigate which trunk of the M2 supplies the central region. Our observations revealed that the trunk at which the central artery originates always courses along part or all of the central insular sulcus. The origin and course of the anterior and posterior parietal and angular arteries also demonstrate special characteristics. Both travel over the long insular gyrus to the posterior insular sulci. The inferior trunk, which supplies the temporal lobe, is preserved. See previous figure legends for abbreviations.

In our specimens we did not observe an accessory MCA, duplication of the MCA, or fenestration of the M1 segment. Several authors have reported observing an accessory MCA, which arises from the ACA, follows a similar course to that of Heubner’s artery, and seldom gives rise to perforating branches. However, cortical branches to the lateral portion of the orbital surface of the frontal lobe have been observed. This variation was observed in 0.3 to 3% of hemispheres according to a number of authors. Yasargil has termed this variation a “false bifurcation.” Because the LLAs characterize the M1 segment, localizing the LLAs and their origins can be important for distinguishing the main MCA bifurcation.

Terminology used to indicate a bifurcation, trifurcation, or quadrifurcation of the MCA generates further confusion. We believe that the MCA has a main bifurcation; however, we wish to supplement our findings and comment on two observations. In 12.5% of hemispheres, the intermediate trunk passed close to the main bifurcation, giving the impression that there was an MCA trifurcation. In 2.5% of hemispheres, both superior and inferior trunks bifurcated immediately after the main bifurcation, giving the impression that there was an MCA quadrifurcation. In cadaver specimens examined by Umansky, et al., the authors observed a bifurcation of the MCA in 66% of hemispheres, a trifurcation in 26%, and a quadrifurcation in 4% of hemispheres. Gibo, et al., observed a bifurcation of the MCA in 78% of hemispheres, trifurcation in 12%, and division into multiple trunks in 10% of hemispheres in their study of cadavers.

In this study we have explored and examined in detail the complex vascularization of the insula. We have endeavored to define, describe, and clarify the intricate vascular patterns and various arterial pathways, with reference to the microsurgical anatomy of this region. We have

Conclusions

In this study we have explored and examined in detail the complex vascularization of the insula. We have
Fig. 6. Photographs of brain specimens. Upper: Arteries of the left insula. Frontal and temporal branches contribute to the vascularization of the insula in the region of the anterior and inferior periinsular sulci, respectively. Lower: The central artery is shown providing branches to the central insular sulcus. aps = anterior periinsular sulcus; ips = inferior periinsular sulcus; pcis = precentral insular sulcus; pis = postcentral insular sulcus; sis = short insular sulcus. See previous figure legends for additional abbreviations.
Arteries of the insula

Fig. 7. Photographs of brain specimens. Upper: The perforator-like insular artery (arrow) supplies the insular apex (ia). Lower: Coronal section is shown of the left cerebral hemisphere through the sylvian vallecula. The perforator-like insular artery (arrow) originates from the M₁ segment and supplies the insular cortex, extreme capsule (exc), claustrum (c), and external capsule (ec). cc = corpus callosum; cg = cingulate gyrus; cn = caudate nucleus; p = putamen. See previous figure legends for additional abbreviations.
done so for the purpose of incorporating, coordinating, and combining this knowledge into the surgical planning process and the surgical procedure to remove a pathological lesion.

Acknowledgments

The authors thank Ching Hearnsberger, R.N., for helping prepare the manuscript and to Ron M. Tribell for his original artistic work.

References

Arteries of the insula


Manuscript received September 23, 1999.
This study was presented in part at the 64th Annual Meeting of the American Association of Neurological Surgeons, Minneapolis, Minnesota, April 27–May 2, 1996.

Address reprint requests to: Ugur Türe, M.D., Marmara University Institute of Neurological Sciences, P.K. 53 Başbuynuy, 81532 Maltepe - Istanbul, Turkey. email: ugurture@turf.net.