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Research

Microsurgical Anatomy of the Insular Region and Its Connections: A Fiber Dissection Study

İnsular Bölgenin ve Bağlantılarının Mikrocerrahi Anatomisi: Bir Fiber Diseksiyon Çalışması

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ABSTRACT

Objective: The insular cortex is a structurally complex and functionally significant brain region, influencing a wide range of neurophysiological processes, including autonomic regulation and emotional cognition. This study aims to provide a detailed analysis of the microsurgical anatomy of the insula and its intricate white matter connections through meticulous fiber dissections of postmortem human brains.

Methods: Four postmortem human brains were preserved in a 10% formalin solution for at least two months. After removing the arachnoid mater, pia mater, and vascular structures, the brains were frozen at -16 °C for at least two weeks. Following rehydration in a 70% alcohol solution at room temperature, white matter dissections were performed using the Klingler technique.

Results: Dissection of the frontal, parietal, and temporal opercula revealed the insula, characterized by an inverted pyramidal shape at the base of the Sylvian fissure. The limen insula, an important anatomical landmark situated deep within the Sylvian fissure, was identified as a crucial reference point in surgical procedures. Upon removal of the insular cortex, detailed structural relationships between the insula, basal ganglia, and white matter tracts were demonstrated.

Conclusion: This study highlights the necessity of advanced surgical precision in addressing insular pathologies to improve neurosurgical outcomes.

Keywords: Insula, fiber dissection, neurosurgery, neuroanatomy

ÖZ

Amaç: Karmaşık bir yapı olan insüler korteks, otonom kontrolünden duygusal bilişe kadar geniş bir yelpazede nörofizyolojik işlevlerde kritik bir rol oynar. Bu çalışma, insülerin detaylı mikroskobik anatomisini ve karmaşık beyaz madde bağlantılarını, postmortem insan beyinlerinin titizlikle lif diseksiyonu yoluyla aydınlatmayı amaçlamaktadır.

Gereç ve Yöntem: Dört postmortem insan beyni, en az 2 ay boyunca %10 formalin çözeltisinde saklandı. Ardından araknoid mater, pia mater ve vasküler yapılar çıkarıldıktan sonra, beyinler en az 2 hafta boyunca -16 °C'de donduruldu. Oda sıcaklığında %70 alkol çözeltisi içinde muhafaza edilen beyinler Klingler yöntemiyle insan kadavraları kullanılarak ak madde diseksiyonları yapıldı.

Bulgular: Frontal, parietal ve temporal operkulum, Silvian fissürünün tabanında yer alan ters piramit şeklindeki insüler yer almaktadır. Silvian fissürünün derininde yer alan ve insülerin anterobazal kısmını oluşturan limen insüler cerrahi açıdan önemli bir alandır. İnsüler korteks kaldırıldıktan sonra insülenin, bazal ganglionlar ve önemli ak madde yolları ile yakın ilişkisi ayrıntılı olarak gösterilmiştir.

Sonuç: Bu araştırma, insüler patolojilerin karmaşıklıklarını daha iyi ele almak ve nöroşirürji alanında hasta sonuçlarını iyileştirmek için gelişmiş cerrahi hassasiyetin kritik gerekliliğini vurgulamaktadır.

Anahtar Kelimeler: İnsula, lif diseksiyonu, nöroşirürji, nöroanatomi

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INTRODUCTION

The insular cortex, a concealed structure deep within the lateral sulcus, is bounded by the frontal, parietal, and temporal opercula. Both experimental and clinical studies have underscored its multifaceted involvement in neurophysiological functions. Studies suggest that the insula plays a crucial role in autonomic regulation, emotional processing, and cognitive functions such as memory, mood, and sensory perception (1,2).

Predominantly affected by low-grade gliomas, the insular region is a common site of pathologies that present with epilepsy. The surgical management of insular gliomas poses significant challenges and a considerable risk of serious morbidity due to their propensity to infiltrate medially into critical paralimbic and limbic structures and laterally into key cortical areas such as the inferior frontal operculum and the supramarginal and angular gyri, particularly in the dominant hemisphere (3). This study meticulously details the microsurgical anatomy of the insula and elucidates its complex interconnections with the surrounding white matter fibers, aiming to enhance the precision and safety of neurosurgical interventions.

The insular cortex, a profound and enigmatic region of the brain, has significant implications for various neurophysiological and neuropsychiatric conditions. As a hub of convergence for sensory, emotional, and cognitive information, the insula orchestrates complex processes ranging from autonomic control to emotional regulation. Recognizing its centrality in human neurology, this study explores the intricate microsurgical anatomy of the insular region and its critical white matter pathways. Our exploration aims not only to delineate the anatomical landscape but also to underscore the clinical ramifications of its pathology, particularly in the context of low-grade gliomas and epilepsy. Such insights are pivotal as they enhance surgical precision and optimize patient outcomes, reflecting the necessity for a profound understanding of this region.

METHODS

Ethics Approval and Registration

Ethics committee approval was not required for this study, as it exclusively utilized cadaveric specimens obtained through authorized commercial sources. In accordance with relevant regulations, studies conducted on such materials do not necessitate ethical review. Since no living patients were involved, obtaining informed consent was not applicable.

Four postmortem human brains were kept in 10% formalin solution for at least (a total of eight hemispheres) months months according to the method of Klingler. After the arachnoid mater, pia mater, and vascular structures were removed, they were frozen at -16 °C for at least two weeks. Then they were rinsed under running tap water and prepared for dissection (4). Between dissections, the brain hemispheres were kept in 70% alcohol solution at room temperature. Dissections were performed under a surgical microscope (Carl Zeiss AG, Oberkochen, Germany) at magnifications of 4× and 40×, using a Rhoton microsurgical set comprising toothless microforceps, a microhook, microscissors, a scalpel, and a dissector. Dissections began with decortication of the lateral and medial surfaces. Following the decortication, short association fibers (U-fibers) were removed and long major association fibers were accessed. Dissections were performed from the lateral to the medial aspect by removing fibers layer by layer. The interrelationships among the fibers and anatomical structures observed at each stage were demonstrated. All stages were recorded using a professional digital camera (Canon EOS 77D) equipped with a Canon 100 mm macro lens, a Canon ring flash, and 3D photography.

Statistical Analysis

This study is a qualitative and descriptive neuroanatomical investigation and does not include any quantitative or comparative dataset; therefore, statistical analysis is not required. As the aim of the study is to delineate microsurgical anatomical structures and demonstrate fiber pathways layer by layer, the use of statistical methods is not methodologically appropriate.

RESULTS

The arachnoid mater and pia mater, fixed using the Klingler method, were cleaned under a microscope using forceps (4). The lateral surfaces of the hemispheres were revealed, showing their cortical structures and all gyral and sulcal structures (Figure 1). Laterally, all cortical gray matter overlying the white matter was removed using dissectors. U-fibers connecting two adjacent gyri were exposed (Figure 2).

Language and Cognitive Connectivity

Long-range association fibers facilitating connectivity between distant cortical areas were visualized, including the superior longitudinal fasciculus (SLF) and the arcuate fasciculus (AF). The SLF was subdivided into SLF II and SLF III, with SLF II originating from the angular gyrus and terminating in the middle frontal gyrus, and SLF III extending from the supramarginal gyrus to the inferior frontal gyrus.

The fibers of the ventral component of the AF originate in the posterior portions of the superior, middle, and transverse temporal gyri [Heschl's gyrus (HG)], make a turn at the level of the posterior insular point, run along the inferior aspect of the supramarginal gyrus just lateral to the corona radiata and along the superior insular limiting sulcus, and extend to the pars opercularis and triangular gyrus within the anterior limiting sulcus of the inferior frontal gyrus. The ventral component of AF was located inferolateral to SLF II and inferomedial to SLF III. SLF II and SLF III were removed, and the dorsal component of the AF was exposed. The dorsal component originated in the posterior one-third of the middle and inferior temporal gyri, turned at the angular gyrus, coursed inferior to SLF II, and terminated in the posterior and middle parts of the middle frontal gyrus, just anterior to the precentral sulcus, similar to SLF II (Figure 3).

The frontal, parietal, and temporal opercula were removed while protecting the HG, thereby exposing the inverted-pyramid-shaped insula located at the base of the Sylvian fissure. The sulci located around the insula, the circular sulcus and the anterior, superior, and inferior limiting sulci, were exposed. The anterior limiting sulcus separated the rostral insula from the inferior frontal gyrus, whereas the superior limiting sulcus separated the upper insula from the superior operculum. The inferior limiting sulcus separates the insula from the posterior part of the Sylvian fissure and the superior temporal gyrus. The limen insula, located deep within the Sylvian fissure and forming the anterobasal region of the insula, emerged as an important landmark.

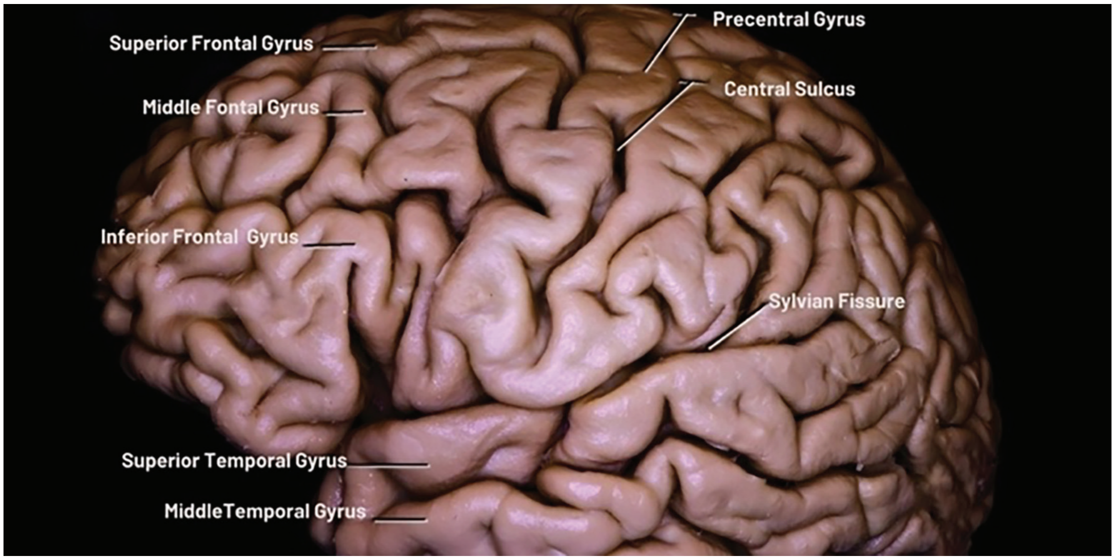

Figure 1. The lateral surface of the cerebral hemispheres

Figure 2. Lateral view of the cerebral hemisphere following the removal of cortical gray matter above the white matter using dissectors. U-fibers connecting adjacent gyri are distinctly visualized

The insula was divided into two parts by the central insular sulcus. The course of this sulcus was parallel to the central sulcus. The central insular sulcus divides the insula into anterior and posterior parts. Three gyri were present in the anterior insula and two in the posterior insula. The gyri anterior to the central insular sulcus are the anterior, middle, and posterior short gyri. The gyri posterior to the central insular sulcus are termed the anterior and posterior long gyri (Figure 4).

Upon removal of the insular cortex, the extreme capsule, which contains short association fibers linking the insula to adjacent opercular regions, was exposed. Further dissections revealed the middle longitudinal fasciculus, originating in the superior temporal gyrus and connecting to the sagittal stratum and the corona radiata. Following removal of the remaining portion of the extreme capsule, a gray layer—the claustrum—and the external capsule fibers associated with this gray matter were

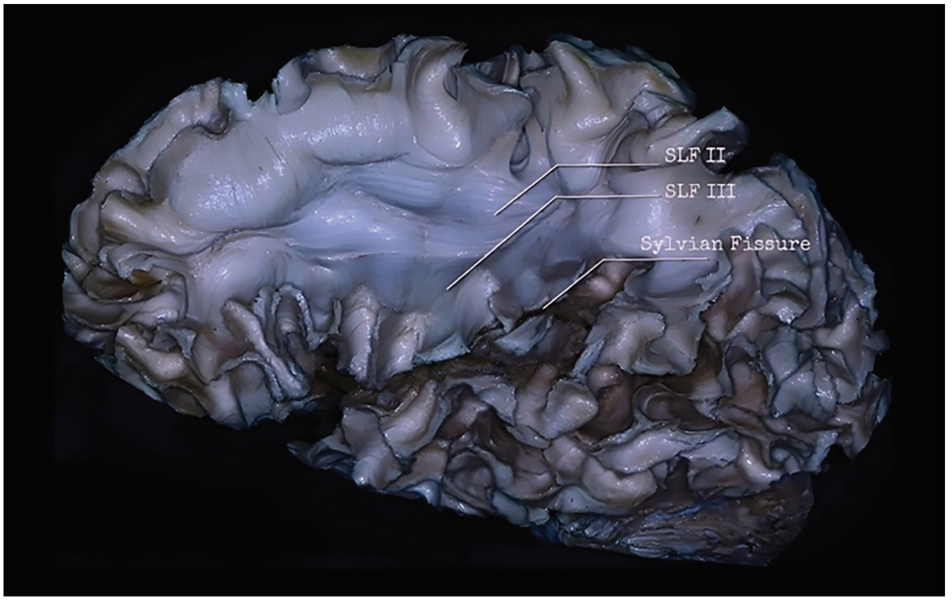

Figure 3. Dissection of the suprasylvian area showing SLF II and SLF III after U-fiber removal. SLF II connects the angular gyrus to the middle frontal gyrus, while SLF III extends between the supramarginal gyrus and the inferior frontal gyrus
SLF: Superior longitudinal fasciculus

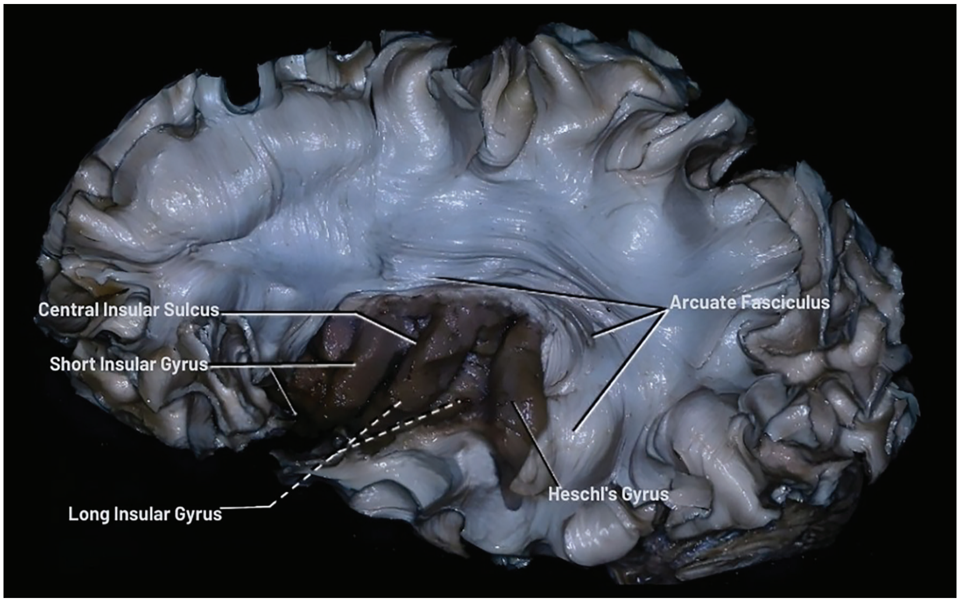

Figure 4. The insula exposed by removing the frontal, parietal, and temporal opercula, preserving Heschl's gyrus. The inverted pyramid-shaped insula, located at the base of the Sylvian fissure and surrounded by the circular sulcus, is visualized. The anterior, superior, and inferior limiting sulci demarcate the insula from neighboring structures. The central insular sulcus, which runs parallel to the central sulcus, divides the insula into anterior and posterior regions, which contain three short gyri and two long gyri, respectively

observed as dorsal and ventral components. Claustrocortical fibers, which constitute dorsal component of the external capsule, were traced to the corona radiata, where they merge with the internal capsule (IC) fibers; their fan-shaped structure extends from the claustrum to the supplementary motor area of the cortex and to the posterior parietal lobe. The ventral component of the external capsule was associated with two fiber bundles: the inferior fronto-occipital fasciculus (IFOF) and the uncinate fasciculus (UF). IFOF fibers were tracked anteriorly to the pars opercularis and pars triangularis within the inferior frontal gyrus. It was observed that the IFOF fibers crossed the AF posteriorly and joined the sagittal stratum. The fibers of the UF originating in the temporal region made a hook-shaped turn at the limen insula and reached the medial orbitofrontal, lateral orbitofrontal, and septal areas (Figure 5).

When the claustrocortical fibers were removed, the putamen, the most laterally located part of the lentiform nucleus (LN), was encountered. When the putamen was gradually removed, another component of the LN, the harder, lighter-colored, rounded globus pallidus (GP), was seen immediately medial to the putamen. The lateral part of the GP was completely covered by the putamen, and it was located lateral to the genu of the IC. The neighborhood of LN, including all IC segments, was shown. The posterior leg of the anterior commissure (AC), running inferior to the LN, was visualized. The posterior crural fibers of the AC were observed to fan out at the lateral border of the LN and to be directed toward their temporal and occipital terminations.

After the SLF, AF, IFOF, and MLF fibers were removed, all parts of the IC were clearly revealed. The IC is a projection fiber bundle and continues its course alongside other fiber bundles that merge beyond the borders of the LN. After this combination, their names change during their journey. At the upper edge of the LN, IC fibers merge with claustrocortical fibers and form the corona radiata. Beyond the posterior border of the LN, it merges with the IFOF, AC, and optic radiation fibers associated with the ventral component of the external capsule and is termed the sagittal striatum. It is the continuation of the corona radiata. The frontal and parietal extensions are called the corona radiata, whereas the occipital and temporal extensions are called the sagittal striatum.

The IC fiber bundle is divided into three sections. These are the anterior limb, the posterior limb, and the genu. The anterior limb of the IC contains bundles of frontopontine and frontothalamic fibers. The IC genu contains the anterior parts of the corticobulbar and corticospinal fiber bundles, and the frontothalamic fiber bundle. The posterior limb of the IC is divided into three parts. These are the lenticulothalamic, retrolenticular, and sublenticular sections. The lenticulothalamic section contains the posterior portions of the corticospinal and corticobulbar fiber bundles, portions of the parietopontine and parietothalamic fiber bundles, and the frontothalamic fiber bundle. The retrolenticular section contains the parietopontine, occipitopontine, occipitothalamic, and parietothalamic fiber bundles.

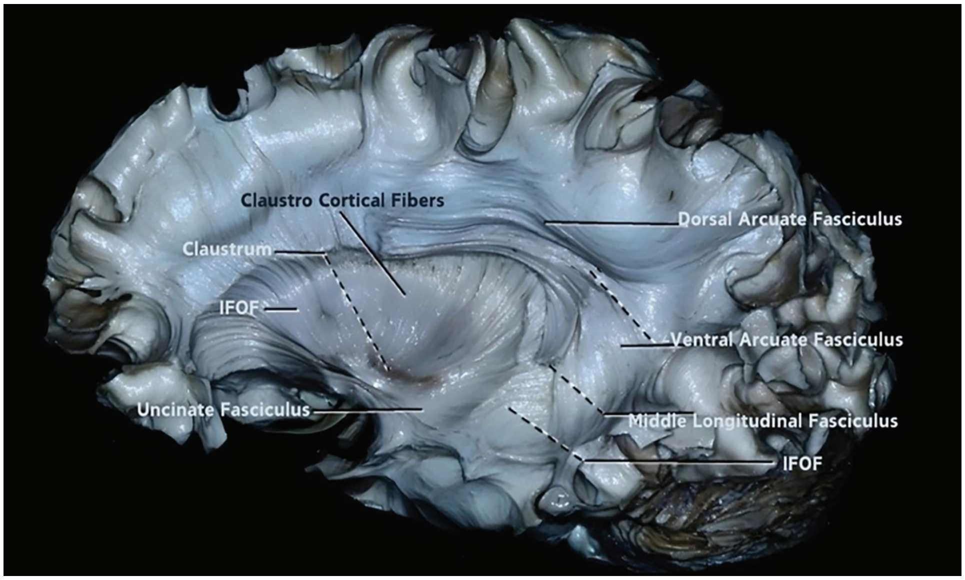

Figure 5. Exposure of the insular cortex revealing the extreme capsule, containing short association fibers connecting the insula with opercular regions. Removal of the extreme capsule exposed the middle longitudinal fasciculus, which originates from the superior temporal gyrus and joins the sagittal striatum and the corona radiata. Beneath the capsule, the claustrum and its associated external capsule fibers were visualized. The dorsal external capsule fibers, or claustrocortical fibers, fanned out toward the corona radiata. The ventral fibers were associated with the inferior fronto-occipital fasciculus (IFOF) and the uncinate fasciculus (UF), with the IFOF crossing the arcuate fasciculus and the UF forming a hook-like turn at the limen of the insula to reach the orbitofrontal and septal regions

The sublenticular section contains temporopontine and temporothalamic fiber bundles, as well as portions of the occipitopontine and occipitothalamic fiber bundles. The optic and auditory radiations are located in the retrolenticular and sublenticular sections of the IC.

AC fibers were observed ventral to the GP. The body of the AC is divided into two parts: anterior (ACa) and posterior (ACp). ACa curled along the nucleus accumbens at the level of the olfactory tract and extended toward the frontal gyrus. The substantia innominata was located between the anterior and posterior limbs of the AC. ACp extended in an anteromedial-to-posterolateral direction within the canal of Gratiolet, located at the base of the LN. The canal of Gratiolet is embedded in the gray matter of the putamen and the caudate nucleus, just anterior and inferior to the border of the GP. Fibers of the ACp extended toward the anterior portions of the temporal and occipital lobes. The number of fibers reaching the occipital lobe was greater than the number reaching the temporal lobe. The fibers extending to the temporal lobe were located inferiorly and merged with fibers of the UF.

Optic radiation fibers emerge from the lateral geniculate nucleus of the thalamus and terminate in the mesial occipital cortex. The dorsal portion of these fibers emerges from the lateral geniculate body and projects directly to the calcarine fissure. However, the ventral fibers initially course anteriorly and then return from the temporal horn to form Meyer's loop. It was observed that the optic radiation fibers, IFOF, and AC fibers destined for the occipital lobe coursed together and merged into the sagittal stratum.

The optic radiation fibers occupy the entire temporal horn, except for the roof and the anterior portion of the lateral wall. When these fibers are removed, the tail of the caudate nucleus, the amygdala, the hippocampus, and the choroid plexus lie together within the temporal horn of the lateral ventricle. When the choroid plexus was removed, the intraventricular hippocampus, located inferomedial to the atrium and temporal horn, was completely visible. The stria terminalis originating from the amygdala and the caudate nucleus tail connecting to the amygdala constituted the deepest layer of the "temporal stem" in the depth of the optic radiation (Figure 6, Table 1).

DISCUSSION

The insula, which is buried deep in the cerebral cortex, has attracted great attention in neuroscience research in recent years (5). The insula has been shown to play roles in memory, mood, autonomic and cardiac regulation, the perception of disgust, and the senses of smell and taste; it is also thought to have many other functions. Changes in the insula have been associated with neuropsychiatric diseases. The anterior insular region, due to its connections with the anterior cingulate gyrus, the dorsolateral prefrontal cortex, the striatum, and the amygdala, mediates autonomic and visceral integration underlying emotional, cognitive, and motivational functions. The posterior insula receives impulses

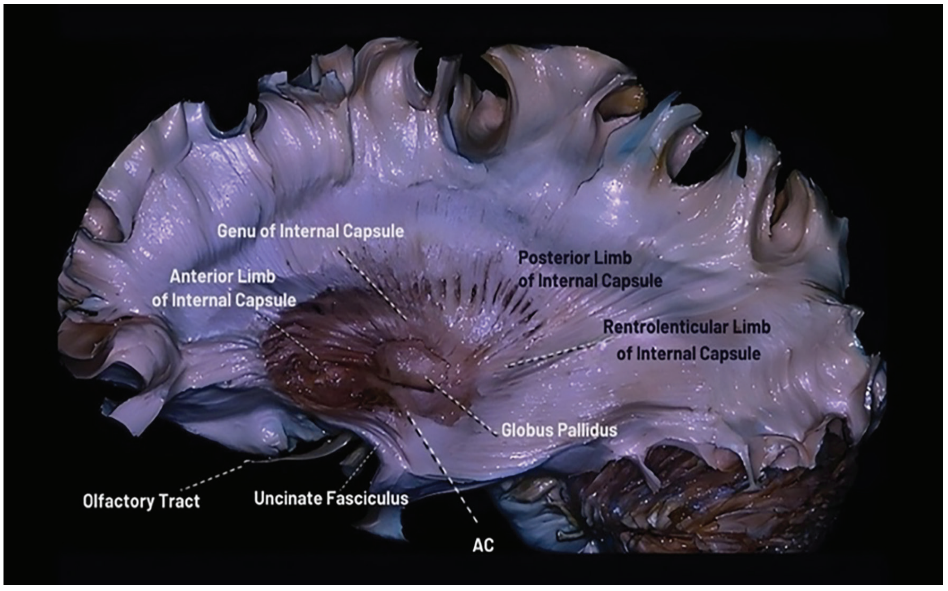

Figure 6. Dissection revealing the lentiform nucleus, internal capsule, anterior commissure (AC), and optic radiation. Removal of claustrocortical fibers exposed the putamen and globus pallidus, components of the lentiform nucleus, and revealed their relationship with segments of the internal capsule. The internal capsule divisions (anterior limb, genu, posterior limb) and associated fiber bundles, including corticospinal, corticobulbar, and thalamic fibers, were demonstrated. The AC was visualized ventral to the globus pallidus, with anterior and posterior components extending toward frontal, temporal, and occipital regions

Table 1. White matter fiber pathways related to the insular cortex: anatomical connections and functional roles

Fiber tract	Origin	Termination	Primary function
U-fibers	Adjacent gyri	Adjacent gyri	Local cortical integration
SLF* II	Angular gyrus	Middle frontal gyrus	Language processing and attentional networks
SLF* III	Supramarginal gyrus	Inferior frontal gyrus	Language production and motor planning
Arcuate fasciculus (ventral)	Posterior superior/middle/ transverse temporal gyri	Pars opercularis and triangularis of the inferior frontal gyrus	Semantic and phonological integration of language
Arcuate fasciculus (dorsal)	Posterior middle and inferior temporal gyri	Middle frontal gyrus (posterior and middle parts)	Repetition and echolalia-related connections
MdLF†	Superior temporal gyrus	Sagittal striatum, corona radiata	Auditory-processing and memory linkage
Extreme capsule fibers	Insula	Opercular areas	Cortex-to-cortex integration
Claustrocortical fibers	Claustrum	Supplementary motor area, posterior parietal cortex	Motor planning and attention networks
IFOF‡	Occipital lobe	Frontal lobe (pars opercularis)	Visual-cognitive and language-orientation pathways
UF	Temporal pole	Orbitofrontal cortex	Emotional memory and semantic association
Anterior commissure	Anterior temporal lobe and olfactory regions and occipital lobe	Contralateral anterior temporal lobe and olfactory regions and occipital lobe	Interhemispheric communication of temporal and olfactory information
Optic radiation	Lateral geniculate body	Calcarine fissure	Visual transmission

*: SLF: Superior longitudinal fasciculus, †: Middle longitudinal fasciculus, ‡: IFOF: Inferior frontal-occipital fasciculus, UF: Uncinate fasciculus

from the brainstem, medulla spinalis, parietal, temporal, and occipital cortices via the thalamus (6,7). In their morphometric study of schizophrenia, Wright et al. (8) found a decrease in gray matter volume in the bilateral temporal region, insula, as well as the left dorsolateral prefrontal cortex and amygdala. Similarly, many morphometric studies have found a relationship between insula volume and schizophrenia (9-11).

The hippocampus, which is closely related to the insula, is an important source of epileptic seizures. It is of great importance for epilepsy surgery, particularly in temporal lobe epilepsy due to hippocampal sclerosis. Microsurgery involving the insula requires a high degree of skill and precision because the insula can be affected by pathologies such as brain tumors, vascular malformations, and epilepsy.

The insula plays an important role in autonomic nervous system function and, owing to its complex structure, regulates emotional, cognitive, and homeostatic processes. Therefore, insular lesions may cause irregularities in cardiovascular function. Additionally, pain signals transmitted through the insula may modulate cardiovascular responses. Somatotopic transmission of painful stimuli via the insula helps us understand potential interactions within the cardiovascular system. Studies have emphasized the role of the insula in pain processing (12). Other studies have reported findings supporting cardiovascular effects associated with insular lesions. Understanding the complex interactions between the insula and the cardiovascular system may represent an important avenue for future research (13).

The insula is a complex structure in the brain that plays a critical role in speech processes and is associated with speech-related white matter fibers. The left insula, in particular, plays a significant role in the production and understanding of language, and in this context, it cooperates closely with Broca's area. The left insula influences speech ability by regulating processes, such as speech planning, motor control, and semantic processing of language (14). AF and SLF, which are white-matter fibers, play an important role in facilitating communication between the insula and other language regions. They connect Wernicke's area with Broca's area and facilitate information exchange between the area that processes language meaning and the area that provides motor control for language. This fiber bundle speech by integrating the cognitive and motor processes of language. The inferior longitudinal fasciculus is associated with language processing of information from the visual and auditory areas and facilitates communication between the insula and other language regions.

Recent advancements in neuroimaging and neuroanatomy have highlighted the insula's pivotal role in integrating somatosensory, gustatory, and visceral inputs, thereby influencing a wide array of bodily functions and emotional responses. The anterior part of the insula, heavily connected with frontal and limbic regions, is crucial for cognitive and emotional processing. In contrast, the posterior insula, linked to sensory pathways, plays a vital role in the perception and contextualization of pain and temperature. The insula's intricate connectivity and multifunctional nature make it a critical consideration in surgical planning, particularly in insular gliomas, where resection can significantly affect the patient's quality of life because of the risk of neuropsychological deficits. Moreover, understanding the insular involvement in autonomic functions underscores its role in disorders like heart disease and dysautonomia, reflecting the need for targeted therapeutic strategies. This discussion extends into neuropsychiatry, exploring correlations between insular abnormalities and mental health disorders such as schizophrenia and depression, highlighting the insula as a potential therapeutic target. Through this comprehensive analysis, we aim to bridge the gap between microsurgical anatomy and clinical practice, providing a foundation for future research and improved surgical interventions.

Study Limitations

Despite the comprehensive anatomical insights provided through meticulous fiber dissections, this study has certain limitations inherent to cadaver-based neuroanatomical research. The number of hemispheres examined was limited, which may reduce the breadth of anatomical variability captured across different specimens. Although the structural relationships and fiber pathways were consistently observed, future studies incorporating a larger number of hemispheres would enhance the generalizability and robustness of these findings. Nevertheless, the detailed layer-by-layer dissections presented here offer a meaningful contribution to the microsurgical understanding of the insular region.

CONCLUSION

The microsurgical anatomy of the insula represents a profoundly intricate and critical domain within neurosurgical practice, essential for the precise diagnosis and management of complex cerebral disorders. Mastery of this region's detailed anatomy, including its vascular and functional components, is paramount to enhancing the safety and efficacy of microsurgical interventions. This comprehensive understanding not only facilitates the minimization of intraoperative risks but also significantly improves postoperative recovery and functional outcomes for patients. The continuous evolution of microsurgical techniques, supported by ongoing research and technological innovations, holds the promise of advancing our capabilities in treating insular pathologies. Thus, as we refine these surgical approaches and deepen our anatomical knowledge, we are poised both to ameliorate the clinical management of insular disorders and to expand the frontiers of our understanding of brain function. This ongoing commitment to research and clinical excellence is crucial for fostering a future where neurosurgical procedures are not only life-preserving but also life-enhancing.

ETHICS

Ethics Committee Approval: Ethics committee approval is not required for studies conducted on commercially sold human cadavers, cadaveric parts, and other biological materials.

Informed Consent: Since no living patients were involved, obtaining informed consent was not applicable.

FOOTNOTES

Authorship Contributions

Surgical and Medical Practices: A.E.A., Concept: A.E.A., M.B., Design: A.E.A., M.B., Data Collection or Processing: A.E.A., M.B., Analysis or Interpretation: A.E.A., M.B., Literature Search: A.E.A., M.B., Writing: A.E.A., M.B.

Conflict of Interest: No conflict of interest was declared by the authors.

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