

Evidence-Based Microsurgical Anatomy of the Temporal Lobe and Temporal Stem: A Systematic Review of the Literature

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ABSTRACT

Introduction: Evidence-based anatomy (EBA) is used to summarize all available data traditionally obtained from individual, often smaller series of or imaging studies into a solid body of evidence. Since its introduction in the early 2010s, this concept has been increasingly used in the field of anatomy, but it is still largely unexplored in micro neurosurgery.

Methods: In this paper, we conducted a systematic review of the literature, using tools such as the PRISMA and PROSPERO recommendations to review the intricate anatomy of the temporal lobe. Were eligible 64 studies for this analysis.

Results: some authors consider the sagittal stratum to be the same group of fibers as the temporal stem, but most consider them different groups; the farther surgeons operate from the temporal pole, the more fiber tracts of the temporal stem are damaged; the temporal lobe contains highly developed areas, especially within the mesial region.

Conclusion: The temporal lobe is a very complex structure and contains highly developed areas, especially within its mesial region. Related disorders require a deep understanding of its anatomy, which is of utmost importance to treating these patients.

Keywords: Anatomy; Cerebral Cortex; Neuroanatomy; Temporal Lobe; Uncinate Fasciculus; White Matter

Abbreviations: EBA: Evidence-Based Anatomy; IFOF: Inferior Fronto-Occipital Fasciculus; MESH: Medicine's Medical Subject Headings; LGN: lateral geniculate nucleus

Introduction

Evidence-based anatomy is the concept of applying the principles and methods of evidence-based medicine and research to the study of human anatomy [1]. It was first introduced in 2014 by Kaissar Yammine [2] as a way to increase the reliability of anatomical studies, which mainly consist of purely descriptive studies. Over the last

decade, efforts have been made to bring this traditionally descriptive discipline into the modern world of evidence-based science [3-5]. The Terminologia Anatomica distinguishes six lobes of the brain: the frontal, temporal, parietal, occipital, insula and limbic lobes [6]. From a microsurgical point of view, the temporal lobe is considered one of the most complex lobes, especially in its mesial aspects [7]

Anatomically, the temporal lobe has three surfaces:

1. A medial surface (commonly referred to as mesial) that faces the midbrain brainstem;
2. A basal surface that faces the floor of the middle fossa; and
3. A lateral surface [8].

Traditionally, the structure of the mesial temporal lobe is described by the connections between the intraventricular, extra ventricular, and adjacent blood vessel systems. The components found within the ventricles include the hippocampus, fimbria, amygdala, and choroidal fissure, whereas those outside the ventricles comprise the uncus, parahippocampal gyrus, and dentate gyrus. The uncus consists of an anterior part, a peak, and a posterior part, which can be divided into an inferior surface and a posteromedial surface; it is positioned medially adjacent to cisternal structures and laterally to the intraventricular components. The anterior part is related to the proximal Sylvian fissure, the internal carotid artery, the M1 segment of the middle cerebral artery, the proximal cisternal anterior choroidal artery, and the amygdala. The peak is associated with the oculomotor nerve, the uncus recess, and the amygdala; the posteromedial surface is related to the P2A segment of the posterior cerebral artery below, the distal cisternal anterior choroidal artery above, and the head of the hippocampus along with the amygdala within the ventricles. The choroidal fissure is situated between the thalamus and fimbria; it originates at the inferior choroidal point behind the hippocampal head and forms the medial boundary of the posterior two-thirds of the temporal horn [7].

The basal or inferior surface of the temporal lobe also consists of three gyri and two sulci, and is connected to the lateral surface by the inferior temporal gyrus. Medially, this gyrus is separated from the fusiform gyrus (also known as the occipitotemporal gyrus or T4) by the occipitotemporal sulcus [8-10]. The medial border of the fusiform gyrus is the collateral sulcus, which marks the lateral border of the parahippocampal gyrus (T5) [8-10]. The lateral surface of the temporal lobe contains three horizontal gyri that run parallel to the Sylvian fissure and are divided by two parallel sulci. The first horizontal gyrus, located immediately below the Sylvian fissure, is called the superior temporal gyrus (T1). This gyrus contributes to the temporal operculum (i.e., the part of the temporal lobe that covers the insula). In its posterior part, the superior temporal gyrus connects to the supramarginal gyrus of the inferior parietal lobe [7]. In the lower region, the superior temporal gyrus is separated from the middle temporal gyrus (T2) by the superior temporal sulcus, a horizontal, sharply delimited, and rarely interrupted sulcus. The middle temporal gyrus, in turn, is separated from the inferior temporal gyrus (T3) by the inferior temporal sulcus [7]. In this study, we performed a systematic review of the literature on the morphological aspects of temporal lobe anatomy to update this topic using a modern approach and specific considerations.

Methods

Search Strategy and Inclusion Criteria

In line with our aim to use a systematic approach to review all available evidence on temporal lobe anatomy, we first established a research protocol in accordance with the updated PRISMA (2020) and PRISMA-P (2015) guidelines [11,12]. Which was subsequently registered in the PROSPERO database (ID CRD42021265386). After preliminary searches to test the best selection of keywords and refine the search strategy, the literature search was conducted between June 1st and August 8th, 2021. Pubmed and ScienceDirect were searched for all peer-reviewed publications from the last fifty years (1971-2021). To reduce the risk of bias, such as location and publication bias, we screened papers regardless of their country of origin, although we limited our search to English-language papers. This was because English was the language understood by all authors and one of the goals of this review was to observe the terms used to define specific structures.

The National Library of Medicine's Medical Subject Headings (MESH) search terms used in the search were: "Temporal Lobe" AND "(anatomy OR structure)", although we added the filter "NOT (epilepsy OR Alzheimer's disease)" in a refined version for the final search. Inclusion criteria included all quantitative and qualitative cadaveric studies, anatomical descriptions and imaging studies that exclusively or primarily addressed the anatomy of the temporal lobe in healthy adults (> 18 years) and were published in peer-reviewed journals. According to the research protocol, all studies that appeared in the initial literature search were screened by title and abstract. Both the search and the screening were conducted independently by two researchers. If disagreements arose, these were resolved between the two researchers and the lead author through discussion until a consensus was reached.

Exclusion Criteria

Single-case reports, letters to the editor, non-peer-reviewed and unpublished studies, studies dealing with pediatric (< 18 years) or non-human specimens or focusing on brains affected by diseases such as epilepsy, Alzheimer's, schizophrenia and other psychiatric disorders were excluded. The quantitative information was recorded using Mendeley software. The data were then exported to Microsoft Excel spreadsheets containing the type of study and its characteristics, such as title, author, year of publication, and journal of publication. Data were recorded in tables by type and publication dates at 5-year intervals between 1971 and 2016, and a 6-year interval between 2016 and 2021. Qualitative information on the anatomical aspects of the temporal lobe was also extracted and a narrative synthesis was conducted performed in order to review the topic. Full information about the research protocol is publicly available via the PROSPERO records.

Results

Literature Demographics

The initial search of the electronic databases yielded 1127 and 1424 entries, respectively, resulting in a total of 2551 studies pre-selected for screening. After a manual review by two independent members of the research team who read titles and abstracts, 2484 papers were deemed ineligible because they either did not meet the inclusion criteria or met the exclusion criteria. Two further studies

were excluded because the full-text was not available in English, and two studies were found to be duplicates, which led to their exclusion. Ultimately, 64 studies were selected for full-text analysis, all of which were eligible for this review ($n = 64$) (Figure 1). The selected studies were then grouped according to the type of study and the date of publication (Figure 2). Most of the available studies were either pure anatomical descriptions or cadaver dissection studies (36), followed by imaging studies (23). None of the articles found employed an evidence-based approach to the study of human anatomy.

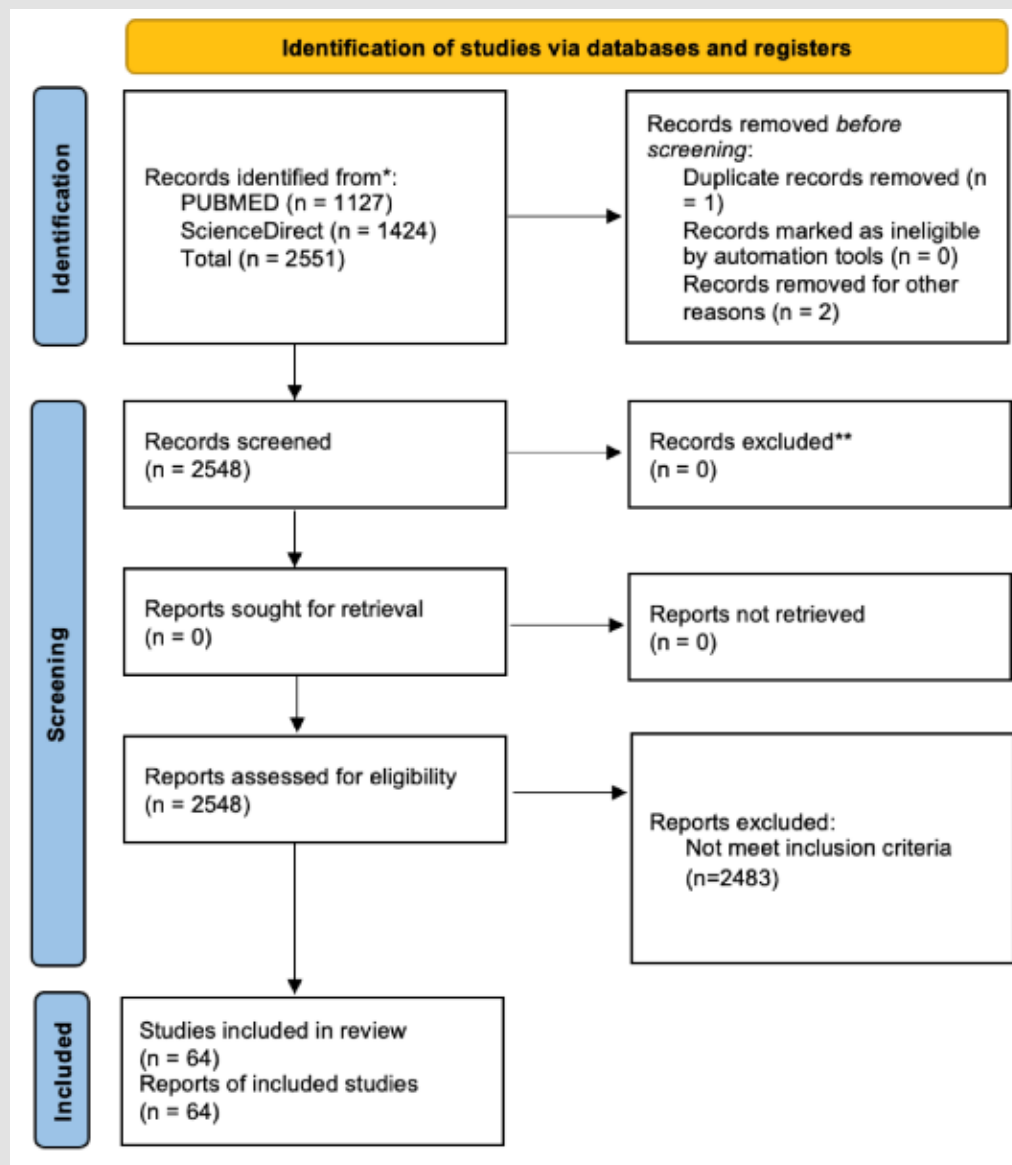


Figure 1: The phases of the systematic review in a PRISMA flow diagram. A total of 2551 studies were preselected for screening; 2484 studies were considered ineligible; two other studies were excluded because the full texts were not available in the English language; and two other studies were found to be duplicates. In the end, 64 papers were retrieved for full-text analysis ($n = 64$).

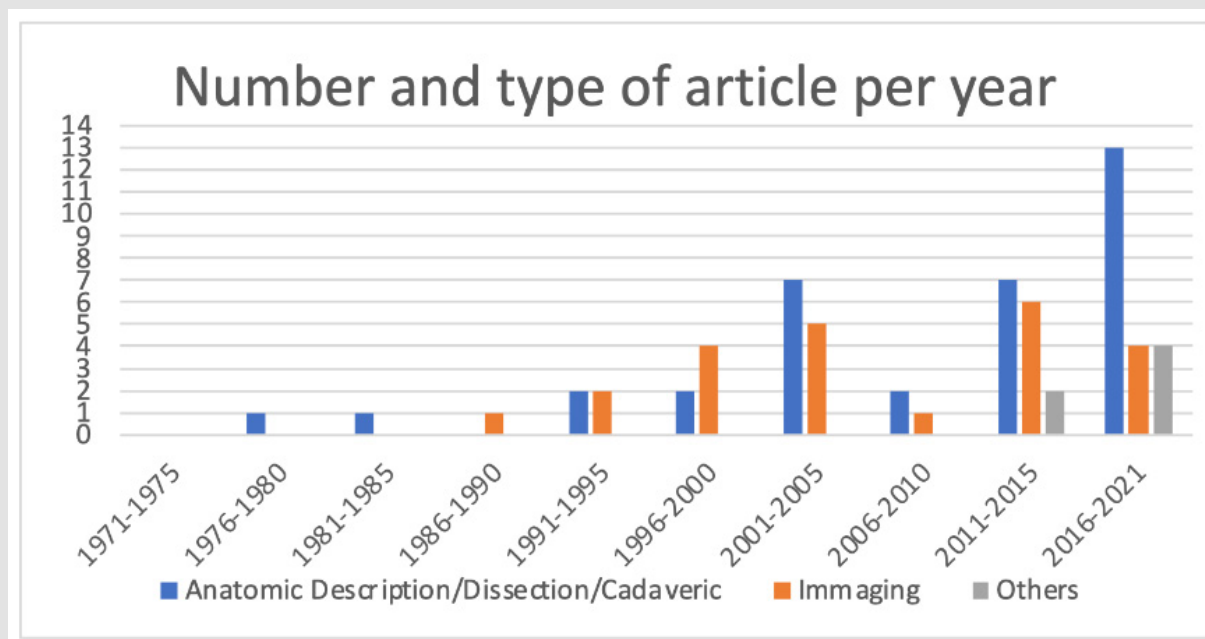


Figure 2: The 64 papers included were grouped by per year and type of article. Most of the available studies were either pure anatomical descriptions or cadaveric dissection studies (36), followed by imaging studies (23).

Microsurgical and Gross Anatomy of the Temporal Lobe

The temporal pole extends to the anterior wall of the middle cranial fossa, which is formed by the greater and lesser wings of the sphenoid bone, separated by the superior orbital fissure. The remainder of the temporal lobe rests on the endocranial surface of the middle fossa. It consists of a base formed by the dura-mater overlying the greater wing of the sphenoid and the petrous portion of the temporal bone, and a lateral wall formed by the greater wing of the sphenoid and the squamosal portion of the temporal bone [8,9]. The temporal lobe is separated from the frontal and parietal lobes by the posterior ramus of the sylvian fissure and its posterior projection, known as the extended sylvian line, and from the occipital lobe by an imaginary line that runs from the lateral impression of the parieto-occipital sulcus to the preoccipital notch [7,9]. Although the separation between the temporal lobe in the lower part and the frontoparietal operculum in the upper part is very clearly defined by the natural border of the sylvian fissure, further back the boundaries between the posterior temporal lobe and the anterior occipital lobe are not as sharp, and remain on the lateral and basal surfaces of the brain [7]. Anatomically, from lateral to medial, beginning at the sylvian fissure, the three surfaces of the temporal lobe consist of 5 gyri, numbered T1 to T5:

T1 – superior temporal gyrus; T2 – middle temporal gyrus; T3 – inferior temporal gyrus; T4 – fusiform gyrus; and T5 – parahippocampal gyrus [10,13,14].

The lateral surface (Figure 3a) of the temporal lobe is best known to the general public and is the region that contributes to the lateral aspect of the brain. This surface is connected to the greater sphenoid wing and the squamous part of the temporal bone. It contains three horizontal gyri that run parallel to the sylvian fissure and are divided by two sulci that are also horizontal. The superior temporal gyrus (T1) contributes with the temporal operculum (i.e., the part of the temporal lobe that covers the insula) and connects superiorly and medially to the three structures that form the opercular surface of the temporal lobe, namely those being the planum polare (a relatively flat region without gyri, which contains a shallow groove for the passage of the sphenoidal segment of the middle cerebral artery), the Heschl's gyrus (the largest and most anterior of the transverse temporal gyri, with functions as the primary auditory cortex) and the planum temporale (formed by the small transverse temporal gyri behind the Heschl's gyrus). In the posterior part, this gyrus connects to the supramarginal gyrus of the inferior parietal lobe, which can be understood as an anatomical continuation of the superior temporal gyrus, as it bends over the posterior ramus of the sylvian fissure [7,9,10].

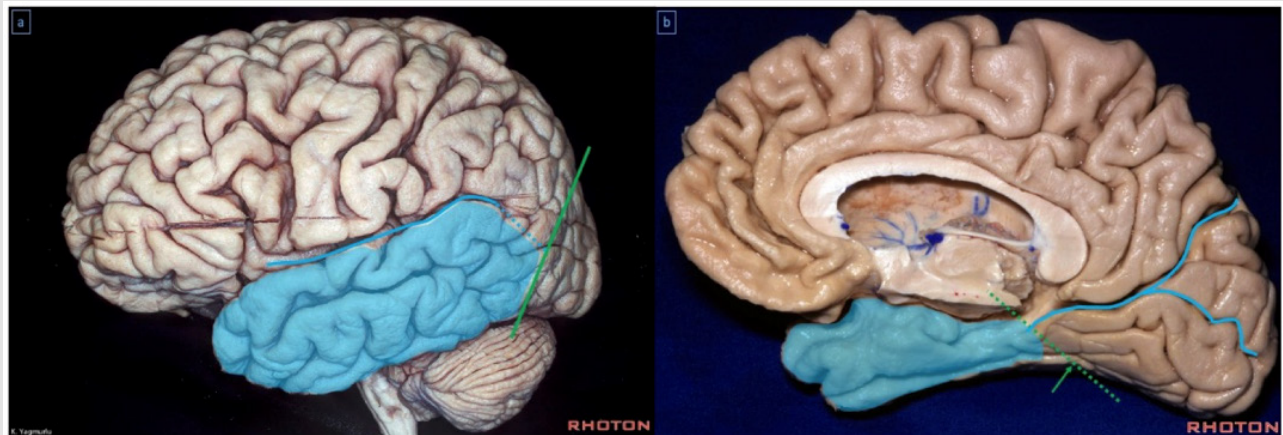


Figure 3: The lateral (3a) and mesial (3b) surfaces of the temporal lobe. On the lateral surface (3a), the temporal lobe is located below the posterior branch of the Sylvian fissure and its extension (parallel Sylvian line) (blue) and in front of an imaginary line that joins the parieto-occipital sulcus to the pre-occipital notch (green line). On the mesial surface (3b), the temporal lobe is located below and medial to the transverse fissure (lateral extension of the ambient cistern) and anterior to an imaginary line (green) that connects the beginning of the calcarine fissure (blue) to the pre-occipital notch (green arrow). The lateral surface (3a) contains three horizontal gyri parallel to the Sylvian fissure, separated by two horizontal sulci. The superior temporal gyrus (T1) contributes to the temporal operculum. Inferiorly, the superior temporal gyrus is separated from the middle temporal gyrus (T2) by the superior temporal sulcus. The middle temporal gyrus is separated inferiorly from the inferior temporal gyrus (T3) by the inferior temporal sulcus. The outer surface of the mesial temporal lobe (3b) is dominated by the parahippocampal gyrus, uncus, and dentate gyrus. At the most anterior region of the parahippocampal gyrus, the mesial temporal lobe is limited by the subarachnoid space at the level of the free edge of the tentorium and the ambient cistern, and is limited laterally by the rhinal sulcus. In its midportion, the surface of the mesial temporal lobe is separated from the diencephalon by the choroidal fissure. The posterior region of the mesial temporal lobe has no clear boundary (dashed green line – the parahippocampal gyrus ends at the point where it is intersected by the anterior-most tip of the calcarine fissure). Courtesy of the Rhoton Collection, American Association of Neurological Surgeons (AANS)/Neurosurgical Research and Education Foundation (NREF) (2021).

In the lower region, the superior temporal sulcus separates the superior (T1) and middle temporal (T2) gyrus, a horizontal, sharply delimited and rarely interrupted sulcus. The middle (T2) and inferior (T3) temporal gyrus are separated by the inferior temporal sulcus, which is highly variable and often an interrupted sulcus. [7,9,10]. The mesial surface of the temporal lobe (Figure 3b) is the most complex in terms of understanding and the surgical approach, but it is also the most important in the context of temporal lobe epilepsy. The outer surface of the mesial temporal lobe is dominated by the parahippocampal gyrus and its corresponding structures, such as the uncus and the dentate gyrus [7, 13]. At the most anterior region of the parahippocampal gyrus, the mesial temporal lobe is bounded by the subarachnoid space at the level of the free edge of the tentorium and the ambient cistern. In the center, the surface of the mesial temporal lobe is separated from the diencephalon by the choroidal fissure, a naturally occurring space formed by the fornix on the outside and the thalamus on the inside.

The posterior region of the mesial temporal lobe has no clear boundary and merges into the mesial surface of the occipital lobe. In this context, it is generally assumed that the parahippocampal gyrus ends at the point where it is intersected by the anterior most tip of the calcarine fissure. It is divided into two parts: a posteroinferior part that connects directly to the lingual gyrus, and a posterosuperior part

that ascends around the splenium of the corpus callosum and merges into as the cingulate gyrus through a small pli de passage known as the isthmus of the cingulate gyrus [7-10,13-15]. The posterior part of the parahippocampal gyrus finds its medial boundary at the anterior edge of the calcarine sulcus and its lateral boundary at the collateral sulcus, which separates it from the fusiform gyrus. Anteriorly, the parahippocampal gyrus is bordered laterally by the rhinal sulcus, which is usually the anterior continuation of the collateral sulcus itself. Medially, the anterior edge of the parahippocampal gyrus folds back on itself like a hook to form a semi-pyramidal, arrow-shaped structure called the uncus. The uncus represents the most medial part of the anterior parahippocampal gyrus on the brain surface [7-10,3-15].

On the outer cortical surface, the uncus is divided into an anteromedial region, an apex, and a posteromedial region. Although it is laterally isolated from the parahippocampal gyrus by the uncal notch in its posterior region, it connects upwards to the globus pallidus and anteriorly to the anterior part of the parahippocampal gyrus proper [15]. The anterior part of the uncus is closely related to the proximal part of the Sylvian fissure, the sphenoidal segment of the middle cerebral artery (M1) and the carotid cistern. The tip of the uncus apex is close to the third cranial nerve (oculomotor nerve), which explains why a mass effect leads to ophthalmoplegia. Finally, the posteromedial part of the uncus is adjacent to the ambient cistern

and the post-communicating segment of the posterior cerebral artery (P2A) [8,9,15]. Deep to the mesial surface of the uncus, and in close association with the intraventricular aspect of the parahippocampal gyrus, the anterior region of the uncus surrounds the amygdala, while its posterior region contains the head of the hippocampus. Therefore, the uncus contributes to the anterior wall of the temporal horn via the amygdala, and to the anterior part of the floor of the temporal horn via the head of the hippocampus [9,15].

From a microsurgical point of view, the uncus can be divided into five small gyri. The anteromedial part of the uncus is formed by the smaller semilunar gyrus at its anterior tip, which is in direct continuation with the rest of the parahippocampal gyrus, and the larger ambient gyrus at its posterior end. Despite its name, the ambient gyrus is not directly related to the homonymous cistern, but is closely related to the posterior part of the carotid cistern. The ambient gyrus is separated from the semilunar gyrus by a shallow indentation, the annular sulcus, and continues posteriorly into the posteromedial uncus, from which it is separated by the uncus notch [15]. The posteromedial part of the uncus consists of three tiny gyri, which are related to the crural and ambient cisterns: the uncinate gyrus, which is the most anterior and is in contact with the ambient gyrus, the band of Giacomini in its center, and the intralimbic gyrus, which forms the posterior end of the uncus. The ambient gyrus and uncinate gyrus converge to form the

uncus apex. They are separated by an imaginary line that connects the uncus notch to the apex [15].

The basal or inferior surface of the temporal lobe (Figure 4) also consists of three gyri and two sulci, and is connected to the lateral surface by the inferior temporal gyrus (Figure 4a), which serves simultaneously as the lower boundary of the lateral surface and as the lateral boundary of the inferior surface. Medially, this gyrus is separated from the fusiform gyrus (also known as the occipitotemporal gyrus or T4) by the occipitotemporal sulcus [8-10] (also known as the lateral occipitotemporal sulcus) [14]. The fusiform gyrus is a well-defined convolution that occupies the center of the basal surface of the temporal lobe and is located directly beneath the ependyma of the floor of the temporal horn of the lateral ventricle (Figure 4b). [7-10]. The medial border of the fusiform gyrus is the collateral sulcus [7-10], sometimes referred to as the medial occipitotemporal sulcus, [14] which marks the lateral border of the parahippocampal gyrus (T5), the last and most medial gyrus of the inferior surface of the temporal lobe [7-10]. The collateral sulcus, one of the most consistent and reliable sulci of the cerebrum [8,9], reaches such a depth that it penetrates the ventricular wall and forms a visible prominence on the floor of the temporal horn, lateral to the hippocampus, called the collateral eminence [8,9,14].

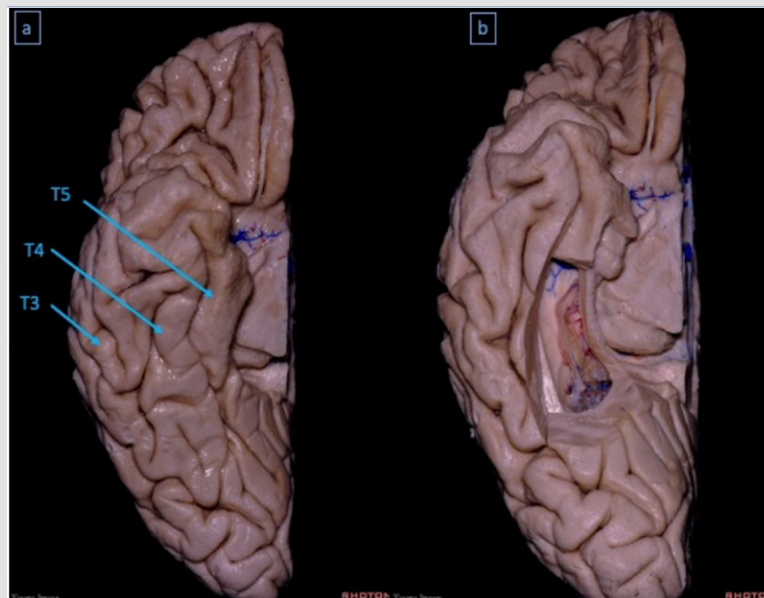


Figure 4: The basal or inferior surface of the temporal lobe. Figure 4a shows three gyri: the inferior temporal (T3), fusiform (T4) and parahippocampal (T5) and two sulci. Figure 4b shows the structures inside the temporal horn of the lateral ventricle, after removing T4 and the posterior portion of T5. In figure 4a, medially, T3 is separated from the fusiform gyrus (also known as the occipitotemporal gyrus or T4) by the occipitotemporal sulcus (also called the lateral occipitotemporal sulcus). The fusiform gyrus occupies the center of the basal surface of the temporal lobe, beneath the ependyma of the floor of the temporal horn of the lateral ventricle (4b). The medial limit of the fusiform gyrus is the collateral sulcus, sometimes referred to as the medial occipitotemporal sulcus, which forms the lateral edge of the parahippocampal gyrus (T5), the most medial gyrus of the inferior or basal surface of the temporal lobe. The collateral sulcus indents the ventricular wall, forming the collateral eminence, a visible prominence on the floor of the temporal horn, lateral to the hippocampus. *Courtesy of the Rhoton Collection, American Association of Neurological Surgeons (AANS)/Neurosurgical Research and Education Foundation (NREF) (2021).*

Similar to the inferior temporal gyrus marking the transition from the lateral to the basal surface of the temporal lobe, the parahippocampal gyrus marks the transition from the basal to the mesial surface of the temporal lobe. Similar to the inferior temporal gyrus, it is simultaneously the most medial boundary of the basal surface and the most basal boundary of the inferior surface of the temporal lobe (Figure 3b). In the depth of the above structures, the temporal lobe fuses with the rest of the hemisphere through a bundle of white matter that extends from the limen insulae to the posteroinferior insular node. This layer of fibers is called the temporal stem because, on coronal sections of the brain, it resembles the trunk of a tree, with gyri T1-T5 representing the branches [10]. The temporal stem can be described as consisting of two parts. An anterior part, formed by the white matter fibers that run under the limen insulae, and a posterior part, formed by the white matter fibers that run under the inferior limiting sulcus. This posterior contingent is called the sagittal stratum. Although some authors consider the temporal stem and the sagittal stratum to be the same group of fibers and use these terms interchangeably [7,15], most authors understand that the term “sagittal stratum” refers only to the bundles of fibers that lie in the depth of the inferior limiting sulcus of the insula. Therefore, they exclude the fibers located anteriorly to it from the sagittal stratum (i.e., fibers that run at the level of the limen insulae belong to the anterior temporal stem, but not to the sagittal stratum) [10,16-20].

White Fibers Classification

At the end of the 19th century, Austrian anatomist Theodor Hermann Meynert [21] proposed a classification system for white matter fibers that divided cerebral axons into three categories:

- a) Association Fibers: axons responsible for the connection of gyri or lobules within the same hemisphere. These fibers can be further subdivided into short association fibers, also called “U fibers” or “arcuate fibers”, which interconnect neighboring gyri, and long association fibers, which are generally grouped into major white-matter tracts or fascicles that connect distant cortical areas;
- b) Commissural Fibers: axons responsible for the interhemispheric connecting of areas across the midline, such as fibers of the corpus callosum, anterior commissure and commissure of the fornix;
- c) Projection Fibers: axons that connect the cerebral cortex to the brainstem and spinal cord [10,16,20-23].

The anterior segment of the temporal stem is formed by the short association fibers of the transverse insular gyrus, the uncinate fasciculus, and fibers originating in the amygdala via the ansa peduncularis. Located directly behind posterior to the uncinate fasciculus and thus deep to the inferior limiting sulcus of the insula, the remainder of the temporal stem is composed by the fibers of the sagittal stratum. This thin lamina of white matter fibers consists of, from superior to

inferior, the inferior fronto-occipital fasciculus (IFOF), the anterior commissure, the posterior and inferior thalamic peduncles (comprising the optic and auditory radiations, respectively) and the tapetum, whose fibers border the ependyma of the atrium and the temporal horn of the lateral ventricle [10,16-20]. Di Carlo et cols. propose that the sagittal stratum consists of three different layers: a superficial layer, consisting of the middle longitudinal fasciculus and the inferior longitudinal fasciculus; a middle layer, consisting of the IFOF; and a deep layer, consisting of the anterior commissure and the optic radiation, beneath these layers lie fibers of the tapetum and the ependyma, which are situated between the sagittal stratum and the ventricular cavity [17]. Using this broader definition of the temporal stem, Ribas et cols divided it into three layers:

1. Superficial Layer: Composed by the extreme capsule, it is the first layer of white matter found immediately deep to the insular cortical mantle. The extreme capsule contains two sets of fibers: short association fibers interconnecting the insular gyri, and association fibers that project from the insular gyri to the medial surface of the opercula.
2. Intermediate Layer: Formed by the external capsule and the anterior commissure. The external capsule is the lamina of white fibers located deep to the medial surface of the claustrum. It is comprised of three distinct bundles: the uncinate fasciculus, the inferior fronto-occipital fasciculus and the claustrorocortical fibers. The anterior commissure is a bundle of commissural fibers organized into a medial cylindrical component (which crosses the midline ventral to the columns of the fornix, connecting the olfactory regions of the frontal lobe and the septal region) and a lateral extension (that runs through a sublenticular canal on the anterior-inferior pole of the globus pallidus called the canal of Gratiolet, connecting both temporal lobes).
3. Deep Layer: Located deep to the lateral extension of the anterior commissure, this layer is composed of the retro- and sublenticular parts of the internal capsule. Medially to the external capsule, the lentiform nucleus and the anterior limb, genu and posterior limb of the internal capsule do not reach the inferior limiting sulcus of the insula; therefore, these structures are not part of the temporal stem. The retrolenticular portion of the internal capsule contains projection fibers that connect the pulvinar and the lateral geniculate body to the parietal and occipital lobes. The bulk of these fibers contributes to the formation of optic radiation, which emerges from the lateral geniculate body and runs posteriorly toward the primary visual cortex within the cuneus and lingual gyrus around the calcarine fissure. The deep layer contains all fibers of the geniculocalcarine tract, including the fibers of Meyer's loop. In turn, the sublenticular part of the internal capsule contains projection fibers originating from the posterior thalamus, specifically the medial geniculate body, which travel to the primary auditory cortex in the anterior transverse temporal gyrus (Heschl's gyrus), constituting the auditory radiation [18].

Microsurgical Anatomy of the Temporal Stem

In this section, we discuss in detail the anatomy of the individual tracts constituting the temporal stem based on different sources [16-20,23-28]. Although this approach is warranted for didactic purposes, it is important to bear in mind that the delimitation and isolation of each tract is not practicable during surgery. Furthermore, even if proper anatomic dissection techniques are used in a laboratory setting, the dissection of one tract generally necessitates the partial destruction of neighboring structures [16,29-32]. Short association fibers, also known as “U fibers” or arcuate fibers, originating from the transverse insular gyrus and the accessory short insular gyrus, constitute the anterior-inferior segment of the extreme capsule and consequently, they contribute to the anterior aspect of the temporal stem, together with the uncinate fasciculus [18]. In 1809, Reil J.C., a German anatomist known for his pioneering description of the insula, first identified the uncinate fasciculus [33].

It is composed of a compact bundle of long association fibers that connect the temporal pole to the orbital cortex of the ipsilateral frontal lobe. The uncinate fasciculus is the smallest of the long association tracts within the temporal stem and owes its name to the steep curvature of its most medial fibers, which impart the tract a hook-like appearance. These same fibers are also responsible for the similar appearance of the limen insulae [24-28]. The uncinate fasciculus is a bidirectional pathway comprising reciprocal fibers linking the anterior temporal lobe (superior temporal gyrus, inferior temporal pole, rostral aspect of the superior temporal sulcus and parahippocampal gyrus), with the ipsilateral orbital region of the frontal lobe, gyrus rectus and rostral cingulate gyrus. Based on its connections between the temporal lobe (including the amygdala) and the frontal lobe (including the anterior cingulate gyrus and pre-frontal cortex), the uncinate fasciculus is considered a functional part of the limbic system. Therefore, it mediates several functions, such as:

- 1) The establishment of emotional responses to auditory stimuli (through fibers from Heschl's gyrus and the rostral superior temporal gyrus);
- 2) Contributions to memory pathways (through fibers from the parahippocampal gyrus);
- 3) The naming of objects and people; and
- 4) Self-regulation and decision-making (through orbitofrontal projections) [28,33,34]. In addition, the uncinate fasciculus is currently under investigation for its potential involvement in the pathogenesis of schizophrenia and several other psychiatric and developmental disorders [28,35-37]. It is also hypothesized that it plays a role in the interictal personality changes observed in patients with temporal lobe epilepsy. Furthermore, damage to the uncinate fasciculus during temporal lobe disconnection procedures might be responsible for the improvement in certain

psychosocial aspects observed in these patients, a hypothesis that remains to be formally tested [28].

The IFOF is a major component of the sagittal stratum. This extensive fasciculus, which interconnects the frontal lobe with the temporal and occipital lobes, is located within the anterior half of the sagittal stratum, deep to the inferior limiting sulcus of the insula. Its fibers cross the temporal stem immediately adjacent to the posterior border of the uncinate fasciculus, connecting the orbitofrontal and pre-frontal regions of the frontal lobe to the posterior temporal cortex and the occipital lobe in a reciprocal fashion [24,25,28]. In addition to its role in visual processing, the IFOF is directly involved in language (specifically through the ventral semantic pathway), a function readily demonstrated during awake craniotomies. During these procedures, direct electrical stimulation of its fibers produces various manifestations of semantic paraphasia, conduction aphasia and speech arrest [24, 25,38-40].

In a series of anatomic dissections using the Klingler technique [22] in ten adult hemispheres, Martino et cols. have shown that the IFOF occupies the posterior two-thirds of the temporal stem, in a position that projects deep to the superior temporal gyrus. It is located, on average, 3.8 mm inferior to the inferior limiting sulcus of the insula and 11 mm posterior to the limen insulae. This corresponds to a distance of 35 mm from the temporal pole and 4.5 mm from the anterior wall of the temporal horn [25,41,42]. The optic radiations, or geniculocalcarine tract, are fibers aggregates that emerge from the lateral geniculate body and the pulvinar of the thalamus to terminate in the calcarine cortex (also called the primary visual cortex or Brodmann area 17). These fibers represent the anatomical extension of the optic pathway, which originates with the axons of the optic nerves and continues through the optic tracts after partial decussation at the optic chiasm [20,26,27]. The fibers of the optic radiation can be divided into three distinct bundles: [20]

- (a) An Anterior Bundle (Meyer's Loop): formed by the most anterior fibers of the geniculocalcarine tract. These fibers follow a recurrent trajectory starting at the anterior aspect of the lateral geniculate body, where they initially follow an anterolateral course along the roof of the temporal horn, lateral to the amygdala. Anterior to the tip of the wall of the temporal horn, they sharply reflect posteriorly, finally terminating in the inferior lip of the calcarine fissure (lingual gyrus). This bundle travels within the lateral wall of the temporal horn and the atrium of the lateral ventricle;
- (b) A central bundle, consisting of fibers that emerge from the central portion of the lateral geniculate body, crossing the roof of the temporal horn in a lateral direction before turning posteriorly. It travels within the lateral wall of the temporal horn, atrium, and occipital horn of the lateral ventricle to reach the lateral occipital pole;

(c) A posterior bundle, composed of fibers that arise from the posterior aspect of the lateral geniculate body and the pulvinar of the thalamus, extending directly to the superior lip of the calcarine fissure (cuneus) through a strictly posterior route within the lateral wall and roof of the atrium and the occipital horn of the lateral ventricle [20].

Discussion

The study of human anatomy was traditionally conducted based on primarily descriptive methodologies, including cadaveric dissections and, more recently, standard imaging studies. While these approaches are fundamental in establishing the groundwork for the subject, they often do not provide the statistical power or level of evidence needed for modern-day science [2-5]. Although the concept of evidence-based anatomical research was proposed almost a decade ago, [2] these studies are still regarded as novel and are rather scarce across the literature, especially in the field of neuroanatomy [32,43-45]. This study adopted an evidence-based approach in the form of a systematic review to synthesize all available evidence concerning the anatomy of the human temporal lobe over the last fifty years. It was observed that there was a paucity of anatomical research on this topic in the last quarter of the 20th century, with only seven papers published from 1971 to 1995. At the turn of the century, the volume of research substantially increased to 18 papers published between 1996-2005 and doubled again, as 36 papers on the subject were published between 2011 and 2021.

This dramatic increase suggests two trends: first, it reflects an increased interest in the development of neuroanatomy as a whole, driven largely by studies on microsurgical anatomy following the introduction of the surgical microscope in the 1980s. Second, it highlights the proliferation of neuroimaging research facilitated by the widespread availability of high-resolution scans enabling the *in vivo* study of central nervous system anatomy. From a neurosurgical perspective, it is important to recognize the peculiarities and safe zones of the temporal lobe. Wen et cols. described that the posterior part of the parahippocampal gyrus appears to be anatomically connected to the occipital lobe through the lingual gyrus at the surface, however, functionally, it is much more closely connected to the limbic lobe through the isthmus of the cingulate gyrus [7]. This region is of utmost importance in the context of epilepsy surgery. Firstly, its anatomical relationship to the external (extraventricular) surface, makes its surgical treatment a complex matter. Secondly, the structures located internally, deep to the mesocortex of the parahippocampal region and on its intraventricular surface, require resection as they are essential for the surgical management of epilepsy [7-10,13-15].

It is necessary to bear in mind that the more posteriorly one proceeds along the temporal lobe axis, the higher the incidence of deficits. This is true for the cortical surface, in the sense that, as resections extend posteriorly into the superior and middle temporal gyri,

they approach to the temporal language complex within the so-called Wernicke's area. In addition, it is also true for white matter resection, since the further the resection extends from the temporal pole, the more fiber tracts of the temporal stem are damaged. A purely anterior temporal resection, such as a standard anterior temporal lobectomy for epilepsy, will most likely damage the fibers of the uncinate fasciculus. However, as the resection is enlarged in a posterior direction, it will subsequently injure the fibers of the sagittal stratum, first at the level of the IFOF and then at the level of the optic radiation. This is also the case for tumor resection in the temporal region, although distances may vary depending on the degree of displacement of the tracts by the tumor mass.

Martino et cols. have shown that during a trans-sylvian approach to the mesial temporal lobe, such as that proposed by Yasargil, [41,42] an incision of the temporal stem 8 mm posterior to the limen insulae will result in a (albeit partial) interruption of the IFOF. On the other hand, during a standard anterior temporal lobectomy, the IFOF is not expected to be injured [25]. Di Carlo et cols. defined the sagittal stratum as a polygonal structure that begins at the junction between the IFOF and the middle longitudinal fasciculus behind the inferior limiting sulcus of the insula, and ends at the vertical occipital fasciculus, with the corona radiata as its upper boundary, with which it then merges. They propose that the sagittal stratum consists of three different layers. A superficial, a middle, and a deep layer, as described in the results [17]. In contrast, Ribas et cols., in a dissection study of 14 adult hemispheres, defined the temporal stem as the contingent of fibers extending from the limen insulae to the inferior limiting sulcus of the insula, a landmark termed the temporal limen point. In addition, the meeting point of the superior and inferior limiting sulci of the insula is known as the posterior insular point, which is an important neurosurgical landmark.

They defined the three layers with different components, as detailed in results [18]. Although a small proportion of fibers synapse within the pulvinar, the pretectal nucleus of the midbrain, and the superior colliculus, the majority of afferent optic tract fibers terminate at the lateral geniculate nucleus (LGN) of the thalamus. From this point forward, all visual sensory information (as opposed to pupillary reflexes, for instance) is transmitted via neurons projecting from the LGN and the pulvinar toward the calcarine cortex [20,26,27]. Párraga et cols. Described the three bundles of the optic radiation as residing within the depth of the superior (T1) and middle (T2) temporal gyri, specifically the deepest layer of the sagittal stratum, approximately 20 mm from the lateral cortical surface and 30 mm posterior to the temporal pole. This anatomical configuration explains why white matter resections extending beyond 30 mm from the temporal pole frequently result in quadrantanopia, while more extensive resections may lead to contralateral hemianopia [20].

This study has some limitations. Since, we prioritized English-language studies, database restrictions (limited to PubMed and Science-

Direct) and the exclusion of non-English studies may lead to publication bias through the omission of relevant data, potentially limiting the generalizability of the findings. We did not utilize a formal quality appraisal tool, such as AMSTAR 2 or ROBIS, as this review focuses on anatomical studies rather than clinical interventions or epidemiological research. Nevertheless, we acknowledge that employing formal quality assessment is essential to mitigate bias. Furthermore, due to inclusion of 64 studies, a summary table listing all individual results would be prohibitively long; therefore, we opted to prioritize conciseness without compromising clarity. However, to summarize the findings, we show here the highlights:

1. Some authors equate the sagittal stratum with to the temporal stem fibers, but most distinguish them as different groups;
2. The farther the surgical approach is from the temporal pole, the more fiber tracts of the temporal stem are damaged; and
3. The temporal lobe houses highly complex anatomy especially within its mesial region.

We encourage further research into EBA-based neuroanatomy to better define surgical challenges and risks, as our study highlights significant neurological risks associated with these fibers. Moreover, future studies should address the lack of consensus regarding anatomical definitions and evaluate evolving surgical techniques.

Conclusion

The temporal lobe is a remarkably complex structure and contains highly developed areas, especially within its mesial region. Associated disorders such as epilepsy and neuro-oncology require a profound understanding of this anatomy iatrogenic neurological deficits. Precise knowledge of these difficult-to-visualize structures is of utmost importance for surgeons to optimize patient outcomes.

Conflict of Interest

The authors declare no conflict of interest in the elaboration or publishing of this paper.

We have received no funding.

Highlights

- There is a lack of evidence-based medicine in the field of neuroanatomy;
- It is the first evidence-based article in temporal lobe and temporal stem in the literature;
- The amount of descriptive research in neuroanatomy increased in the last decade;
- Some authors considerate sagittal stratum the same group of

fibers to the temporal stem, but most considerate different groups;

- The farther the surgeons get from the temporal pole, the more fibers tract of the temporal stem are damaged;
- The temporal lobe contains highly developed areas, especially within the mesial region.

Author Contributions

All authors verified the analytical methods. All authors discussed the results and contributed to the final manuscript. RNB, CRS, CAM, LdeP, PAF, RFB wrote the manuscript with support from ZDJr and BC. RNB and ZDJr supervised the project. RNB, ZDJr PAF and RFB took the lead in writing the manuscript. CRS, CAM, LdeP, BC provided critical feedback and helped shape the research, analysis, manuscript and pictures RNB, CRS, ZDJr, LdeP, RFB, BC worked out almost all of the technical details. RNB, RFB wrote the final version of the paper with input from CRS, ZDJr, CAM, LdeP, PAF, BC reviewed the final version and implemented their final input. All authors took part in all topics (introduction, methods, results, discussion, conclusion).

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