ORIGINAL ARTICLE - NEUROSURGERY GENERAL

Microsurgical anatomy of the sagittal stratum

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Abstract

Background The sagittal stratum (SS) is a critical neural crossroad traversed by several white matter tracts that connect multiple areas of the ipsilateral hemisphere. Scant information about the anatomical organization of this structure is available in literature. The goal of this study was to provide a detailed anatomical description of the SS and to discuss the functional implications of the findings when a surgical approach through this structure is planned.

Methods Five formalin-fixed human brains were dissected under the operating microscope by using the fiber dissection technique originally described by Ludwig and Klingler.

Results The SS is a polygonal crossroad of associational fibers situated deep on the lateral surface of the hemisphere, medial to the arcuate/superior longitudinal fascicle complex, and laterally to the tapetal fibers of the atrium. It is organized in three layers: a superficial layer formed by the middle and inferior longitudinal fascicles, a middle layer corresponding to the inferior fronto-occipital fascicle, and a deep layer formed by the optic radiation, intermingled with fibers of the anterior commissure. It originates posteroinferiorly to the inferior limiting sulcus of the insula, contiguous with the fibers of the temporal stem, and ends into the posterior temporo-occipito-parietal cortex.

Conclusion The white matter fiber dissection reveals the tridimensional architecture of the SS and the relationship between its fibers. A detailed understanding of the anatomy of the SS is essential to decrease the operative risks when a surgical approach within this area is undertaken.

Keywords Microsurgical anatomy · Fiber dissection · Optic radiation · Sagittal stratum · White matter

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Introduction

The sagittal stratum (SS) is a large white matter sagittal structure located laterally to the atrium of the lateral ventricle [16]. This region is an important cross-road due to the presence of major white matter tracts [3, 24]. The inferior fronto-occipital fascicle (IFOF) and the optic radiation (OR) form the main bundles of the stratum [28, 38]. Recent studies based on diffusor tensor imaging (DTI) analysis suggest the inclusion of the inferior longitudinal fascicle (ILF), and the middle longitudinal fascicle (MdlF) in the SS [2, 17]. The MdlF is located medial to the arcuate fascicle (AF), above the IFOF, and extends to the superior temporal gyrus (STG) [19]. The ILF runs laterally and inferiorly to the lateral wall of the temporal horn, connecting the occipital lobe with the anterior part of the temporal lobe [17]. Nonetheless, its existence as a fascicle itself was frequently questioned in the last few decades [29, 30, 39]. Accordingly, the anatomy of the SS is not well

understood, and several anatomical questions remain unresolved. Recently, the use of direct electrical stimulation (DES) during surgical resection of intrinsic tumors [3] suggested that this structure is involved in verbal and non-verbal language processing [5], reading and visual recognition [3, 20], and visual information [6]. The objectives of this study are to define the anatomical limits of the SS, obtain reliable landmarks to differentiate the different bundles of the stratum, and finally to discuss its functional implications.

Materials and methods

The study was approved by the ethical committee of the Faculty of Medicine of our University, and the specimens were obtained in the first 12-h postmortem from donors without clinical history of neurological disease.

Five formalin-fixed human brains were dissected under the operating microscope (× 3–40 magnification) by using the fiber dissection technique described by Ludwig and Klingler [16]. The brains were fixed in 10% formalin for at least 1 month. Subsequently, the arachnoid membrane and vascular structures were removed, and the brains were frozen at − 15 °C for 15 days. Cerebral sulci and gyri were studied and photographed in each specimen. Thereafter, hand-made wooden spatulas of various sizes were used to peel away both the cortex and the short "U" association (intergyral) fibers. In four specimens, lateral dissection of the hemisphere was performed [8, 38] while preserving the insular cortex, the temporal pole, and the superior parietal lobule (SPL). The AF and the superior longitudinal fascicle (SLF) were exposed. Thus, we cut and removed the AF-SLF complex [19] at the level of its intersection with the superior limiting sulcus of the insula, preserving the vertical occipital fascicle (VOF). Then, to expose the MdlF, the dissection continues as described by Maldonado et al. [19], starting from the superior temporal gyrus (STG), preserving the temporal pole. Afterwards, the IFOF and the UF were exposed. The last step of the lateral dissection aimed to isolate the anterior commissure (AC) and the posterior thalamic peduncle [9], removing the IFOF, the UF, and part of the anterior perforated substance. The basal surface was dissected up to the floor of the temporal horn, to identify the posterior thalamic peduncle as described by Goga et al. [9]. In order to delineate the anterior limit of the SS, we measured the mean distance between the temporal pole and the intersection between the IFOF and the MdlF. The fifth brain was cut at the level of the trigone of the lateral ventricle parallel to the coronal plane. Subsequently, stepwise lateral dissection was performed in order to observe the layers of the SS from a coronal point of view.

Results

Cerebral sulci and gyri

The lateral surface of the brain and the main cortical sulci and gyri are shown in Fig. 1.

Limits of the sagittal stratum

The SS can be assimilated to a polygon (Fig. 2), located posteriorly to the inferior limiting sulcus of the insula. In all dissections, the junction between the IFOF and the MdlF identified the anterior limit of the SS. The distance between the temporal pole to this intersection was 36.38 ± 7.43 mm (Fig. 2b). As further discussed, at the level of the temporal horn, an ILF contingent runs in the inferior part of the SS. Thus, the dorsolateral occipital segment of the ILF delineated the most inferior part of the SS (Figs. 2a and 3). Posteriorly, before cortical termination to the occipital lobe, the VOF, connecting the ventrolateral to the dorsolateral visual cortex, limits the SS (Figs. 2a, c and 4). It lies on the superolateral walls of the temporal horn, the atrium, and the occipital horn of the lateral ventricle and is separated from the ependyma by the tapetal fibers of the corpus callosum (Fig. 5). The corona radiata and the SS were contiguous to each other at the level of the posterior insular point [37] (Fig. 2a, c), and, after the removal of the external capsule and the putamen, it is possible to observe the retrolenticular portion of the internal capsule running in contiguity to the middle and the deep layer of the SS (Fig. 5a, b). The lateral limit of the stratum was the AF-SLF (Fig. 4).
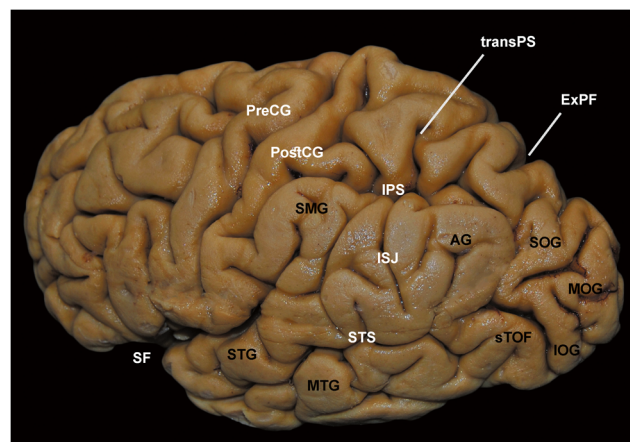

Fig. 1 Cerebral sulci and gyri of the lateral surface of the brain. AG, angular gyrus; ExPF, external perpendicular fissure; IOG, inferior occipital gyrus; IPS, infra-parietal sulcus; ISJ, intermediate sulcus of Jensen; MOG, middle occipital gyrus; PostCG, post-central gyrus; PreCG, pre-central gyrus; SF, Sylvian fissure; SMG, supra-marginal gyrus; SOG, superior occipital gyrus; STS, superior temporal sulcus; STG, superior temporal gyrus; transPS, transverse parietal sulcus of Brissaud; sTOF, superior temporo-occipital fold
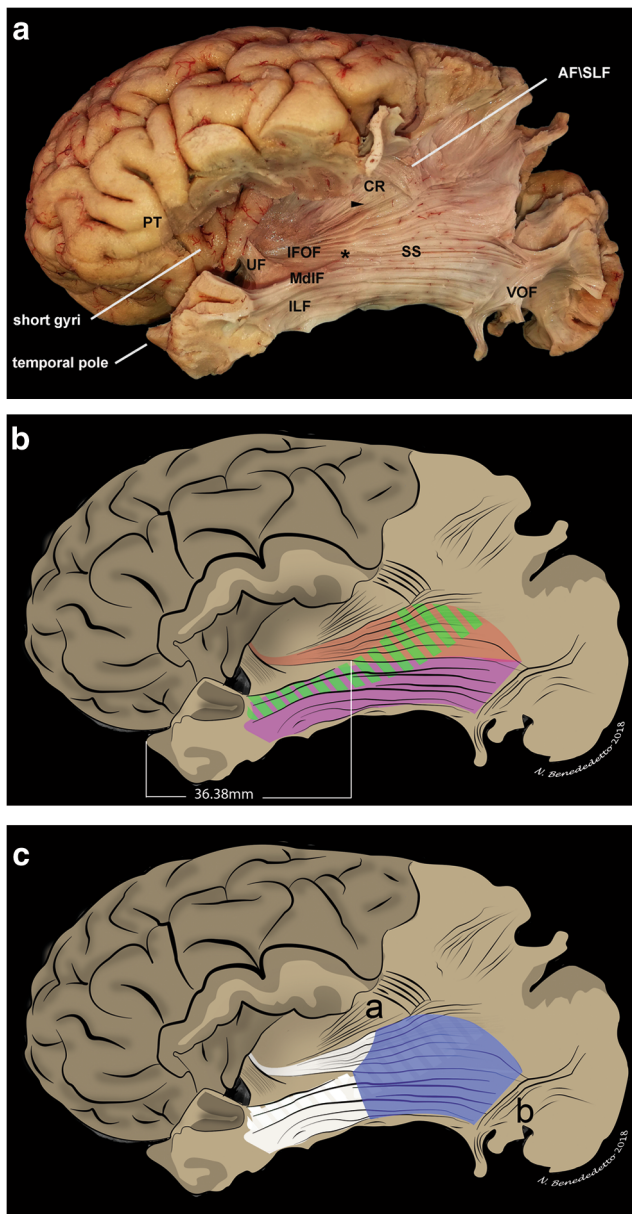
fascicle runs under the transverse temporal gyri in a caudocranial and lateromedial direction. It passes below the AF-SLF complex and terminates beyond the inferior parietal lobule (IPL), in the lateral aspect of the occipital lobe, close to the ExPF (Figs. 3 and 6a, b).

The inferior longitudinal fascicle

The ILF runs lateroinferiorly to the temporal horn of the lateral ventricle connecting the occipital lobe to the anterior temporal region (Fig. 2a). Four components were observed: the dorsolateral occipital segment, the fusiform segment, the lingual segment, and the cuneal segment. The dorsolateral portion connects the dorsolateral occipital cortex to the temporal lobe (Figs. 2a, 3, and 6a). After removing this bundle, we isolated the cuneal branch in 83% of the hemispheres. The dorsolateral occipital segment is in relation to the MdlF, and it was not possible to differentiate the two white matter tracts in the inferolateral part of the SS (Fig. 2a, b). Accordingly, we observed that an ILF contingent runs within the inferior part of the SS (Figs. 2a, b and 7).

Middle layer of the sagittal stratum

The IFOF is the middle layer of the SS (Fig. 7). It was exposed after the removal of the MdlF and the ILF (Fig. 6c). It originates from the frontal lobe and runs under the anterior limiting sulcus of the insula, superiorly to the uncinate fascicle, in the external capsule (Figs. 3 and 6b). It passes through the ventral claustrum (with the UF) and continues posteriorly, passing under the inferior limiting sulcus of the insula, directed to the posterior part of the temporal, parietal, and occipital lobes (Figs. 2a, b and

Layers of the sagittal stratum

We defined three layers of the sagittal stratum: (1) superficial layer: MdlF and ILF; (2) middle layer: IFOF; (3) deep layer: AC and the OR. Stepwise dissection of the lateral aspect of the SS is shown in Fig. 6 a–g, and a coronal view of the three layers is provided in Fig. 7 a–e. A schematic representation of the SS is shown in Fig. 8.

Superficial layer of the sagittal stratum

The middle longitudinal fascicle

In 83% of the hemispheres, we isolated a long white matter tract originating from the anterior third of the STG. This
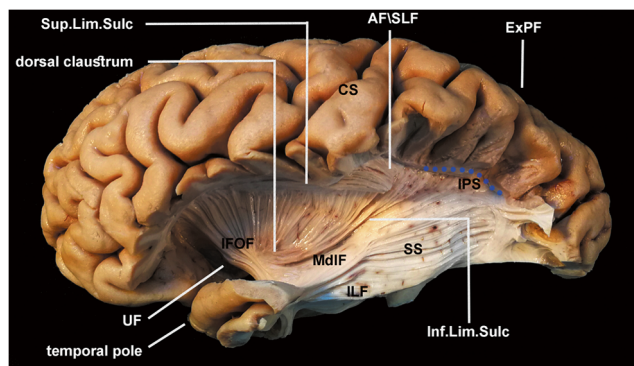
Fig. 3 The MdlF runs from the anterior third of the STG directed toward the parietal lobe. It is contiguous to the dorsolateral occipital portion of the ILF that runs from the anterior temporal region to the dorsolateral occipital cortex. The IFOF is cranial to the UF at the level of the temporal stem. It continues posteriorly directed to the posterior part of the temporal, parietal, and occipital lobe. AF, arcuate fascicle; CS, central sulcus; ExPF, external perpendicular fissure; ILF, inferior longitudinal fascicle; Inf., inferior; IFOF, inferior fronto-occipital fascicle; IPS, infra-parietal sulcus (blue dotted line); Lim., limiting; SLF, superior longitudinal fascicle; Sulc., sulcus; Sup., superior; SS, sagittal stratum; UF, uncinated fascicle

6b, c). Inferiorly to the inferior limiting sulcus of the insula, the MdlF and the IFOF cross each other (Figs. 2a, b and 3). Subsequently, it joins the SS and divides into two branches: a superficial one that lies on the lateral surface of superior part of the atrium reaching the parietal and occipital cortex, and an inferior portion that runs superficially to the posterior thalamic peduncle, in the roof of the temporal horn, directed to the posterior temporal and occipital cortex (Figs. 2a, 6c, and 7b).
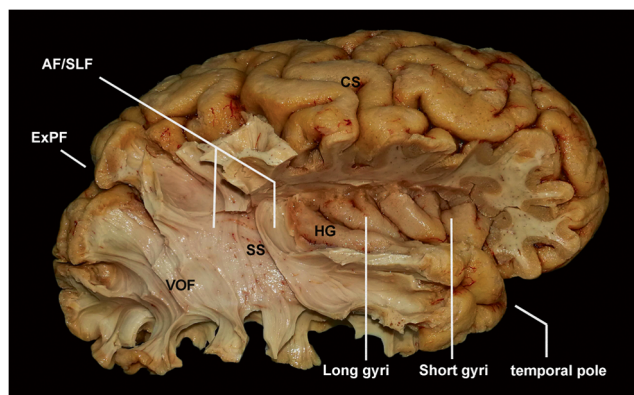

Fig. 4 The insula and the Heschl's gyrus are exposed after the removal of the frontoparietal operculum. The AF/SLF complex is partially peeled away to show its topographical relationship with the SS, which is just medial to this fiber tract. The VOF, connecting the ventrolateral to the dorsolateral occipital cortex, limits the SS posteroinferiorly. AF, arcuate fascicle; CS, central sulcus; ExPF, external perpendicular fissure; HG, Heschl's gyrus; SLF, superior longitudinal fascicle; SS, sagittal stratum; VOF, vertical occipital fascicle

Deep layer of the sagittal stratum

The anterior commissure

The AC was exposed in the last step of the lateral dissection, after the removal of the IFOF, the UF, the amygdala, the hippocampus, and part of the anterior perforated substance (Fig. 6d). Accordingly, it was possible to isolate the "handlebar" component of the AC, just ventral to the columns of the fornix. The lateral expansion of the AC lies above the substantia innominata and inferomedially to the IFOF, covered by a thin layer of white matter called the canal of Gratiolet. This bundle continues posteriorly within the temporal stem (Fig. 6d) [32]. Then, one branch joins the posterior thalamic peduncle within the SS (Fig. 6d), the other branch merged to the UF directed at the temporal lobe.
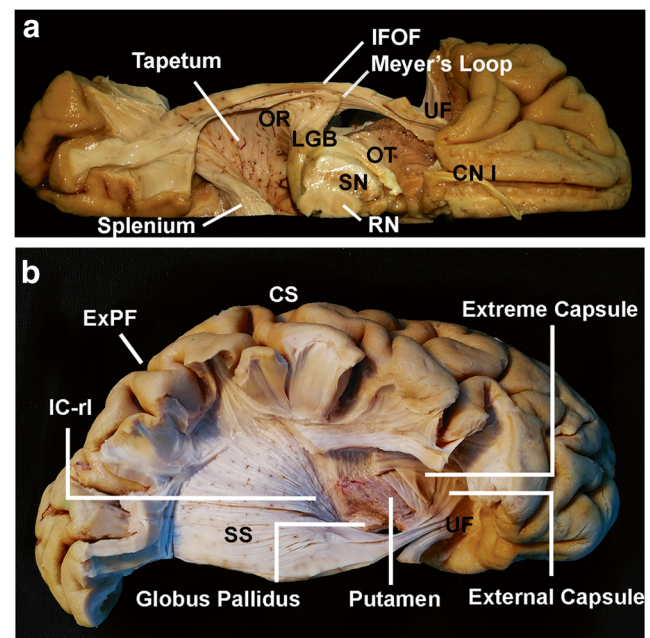

Fig. 5 The same specimen is captured from two different prospective showing the relationship between the corticofugal projection fibers coming from the posterior and mesial parietal lobe and the SS. Furthermore, the origin and the course of the OR are described. **a** The fibers of the OR, originating from the LGB, loop from anterior to posterior, directed to the occipital cortex. The fascicle runs on the roof of the temporal horn and the lateral wall of the atrium, separate to the ventricle by the tapetum. The IFOF runs above the OR that is the main component of the deep layer of the SS. **b** The lateral surface of the hemisphere and the insula are dissected preserving the extreme capsule, the external capsule, and the retrolenticular portion of the internal capsule. The projection fibers limit superiorly the SS. Cap., capsule; CS, central sulcus; CN I, cranial nerve I; ExPF, external perpendicular fissure; IC-rl, internal capsule retrolenticular portion; IFOF, inferior fronto-occipital fascicle; LGB, lateral geniculate body; OR, optic radiation; OT, optic tract; RN, red nucleus; SN, substantia nigra; SS, sagittal stratum; UF, uncinated fascicle.
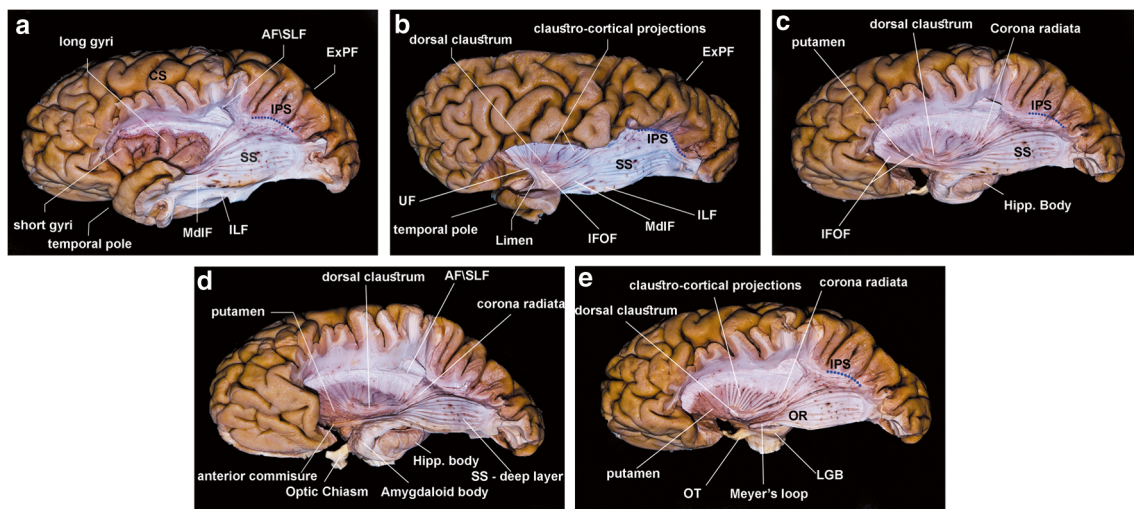
Fig. 6 Stepwise dissection of the SS, demonstrating the topographic anatomy and the layers of the stratum. The IPS is represented as a blue dotted line after removal of the inferior parietal lobule. **a** The frontoparietal operculum was removed to expose the insula and the dissected temporal lobe. The IPS was the superior limit of the dissection. After removal of the "U" fibers, the AF/SLF complex was peeled away exposing the superficial layer of the SS (MdlF and ILF). **b** The insular cortex and extreme capsule were removed. The IFOF and the MdlF cross each other defining the anterior limit of the stratum. **c** The middle layer of the SS is exposed. The IFOF, after passing into the temporal stem, joins the SS directed toward the temporo-parieto-occipital cortex. **d** The substantia innominate was removed exposing the AC and its lateral extension. This fascicle passes through the basal portion of the putamen and the globus pallidus within the temporal stem, and joins the deep layer of the SS, intermingled with the OR. **e** The last step of the dissection shows the LGB and the course of the OR directed toward the occipital cortex. AF, arcuate fascicle; AG, angular gyrus; CS, central sulcus; ExPF, external perpendicular fissure; Hipp., hippocampus; ILF, inferior longitudinal fascicle; IFOF, inferior fronto-occipital fascicle; IPS, infra-parietal sulcus; ISJ, intermediate sulcus of Jensen; limit., limiting; MdlF, middle longitudinal fascicle; MOG, middle occipital gyrus; SF, Sylvian fissure; SLF, superior longitudinal fascicle; SMG, supra-marginal gyrus; SS, sagittal stratum; STG, superior temporal gyrus; STS, superior temporal sulcus; sup., superior; UF, uncinate fascicle

The posterior thalamic peduncle—the optic radiation

The OR originates from the lateral geniculate body as part of the posterior thalamic peduncle. Together with the auditory radiations, temporal and occipital projections, they cannot be differentiated at the level of the LGB (Figs.5 and 6e). The OR is the deep layer of the SS and lies on the roof of the temporal horn, the lateral wall of both the atrium and the occipital horn (Figs. 7c and 8). It terminates along the calcarine fissure and the lateral aspect of the occipital lobe [25]. The anterior portion of the OR follows an anterolateral direction along the roof of the temporal horn, shifting backwards in a posterolateral course, forming the Meyer's loop (Fig. 5). A contingent of fibers originating from the occipito-temporal cortex and directed to the brainstem underneath the OR has not clearly been observed in the coronal cut (Fig. 7a). Accordingly, it was not possible to separate these fibers within the deep layer of the SS neither in the sagittal nor in the coronal dissection (Fig. 7d, e).

Discussion

"A legacy of incertitude surrounds the definition of SS, and the nature of its constituent fibers" stated Schmahmann and Pandya, introducing the SS, in their book "Fiber pathways of the brain" [34]. The first identification of a fiber system connecting the occipital and temporal lobes was reported in the early nineteenth century [31]. This structure was named ILF and defined as an association fiber system. In 1892, Heinrich Sachs observed the peculiar parasagittal orientation of this bundle of axonal fibers in the posterior regions of the hemisphere and named this structure *sagittal stratum* [33]. According to Sachs, the SS was divided into an internal corticofugal segment, and an external corticopetal segment from the thalamus [33], in which the ILF was included. After the work of Polyak, Flechsig, Meyer, and Burdach [1, 23, 29, 40], the SS was considered synonymous with the OR, and the existence of a direct occipito-temporal connection (the ILF) was repeatedly questioned [29, 30, 39]. In their monumental work on non-human primate brains, Pandya et al. observed that the posterior limb of the internal capsule is bounded posteriorly by the SS [34]. Their investigation showed that the stratum is a major subcortical fiber system that conveys reciprocal information between the posterior aspect of the hemisphere and the thalamus and brainstem structures. Accordingly, they concluded that the stratum was not exclusively a fiber tract connecting the LGB with the calcarine cortex. A robust body of evidence suggested that the SS could be divided in an internal and an external portion [13, 15, 34]. This dichotomization, based on histological and MRI studies, describes only the deep layer of the SS, labeling all the superficial fascicles as "adjacent white matter" [15]. During the last
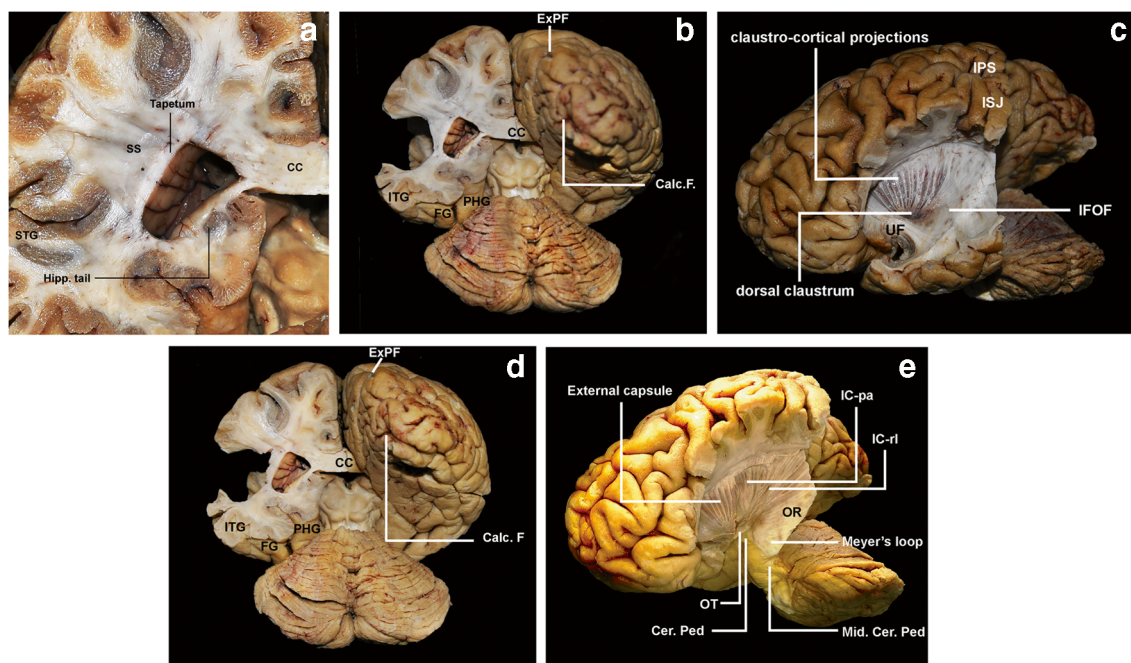
Fig. 7 a The difference between the corticofugal projection fibers directed to the brainstem and the OR is not clear on the specimen in which we can observe a grayish (*asterisks*) layer just lateral to the tapetum representing the deep layer of the SS. **b** and **c** After the removal of the superficial layer of the SS, the IFOF is revealed confirming that the middle and the deep layer (**d**) of the SS are in close relationship. **e** The posterior thalamic peduncle is exposed; the OR can be observed in contiguity to the internal capsule. The differentiation between the corticopontine fibers and the OR was not possible with the fiber dissection technique at the level of the SS. Calc., calcarine; Cer. Ped, cerebral peduncle; CC, corpus callosum; Hipp., hippocampus; ExPF, external perpendicular fissure; IC-pa, internal capsule posterior arm; IC-rl, internal capsule retrolenticular portion; IFOF, inferior fronto-occipital fascicle; IPS, inferior parietal lobule; ISJ, intermediate sulcus of Jensen; ITG, inferior temporal gyrus; FG, fusiform gyrus; Mid. Cer. Ped, middle cerebral peduncle; OT, optic tract; PHG, parahippocampal gyrus; STG, superior temporal gyrus; SS, sagittal stratum; UF, uncinate fascicle.

decades, general consensus was gradually achieved regarding the participation of the IFOF in the SS [16, 25, 27, 32, 35, 38]; nonetheless, the debate regarding its boundaries and its topographic anatomy is still open.

Morphological characteristics of the sagittal stratum

The SS is a bundle of associational fibers situated deep on the lateral surface of the hemisphere, laterally to the tapetal fibers of the atrium [3, 34]. It originates posteroinferiorly to the inferior limiting sulcus of the insula, contiguous with the fibers of the temporal stem [32]. It ends into the posterior temporo-occipito-parietal cortex and presents a polygonal shape. The intersection between the MdlF and the IFOF is roughly 35 mm from temporal pole, inferiorly to the inferior limiting sulcus of the insula. At this level, the fibers of these fascicles mingle with each other forming the anterior limit of the SS. Then, it continues posteriorly contiguous in its superior and dorsal aspect to the corona radiata. The fibers directed to the posterior parietal region form the superior portion of the SS [34]. Our results demonstrated that the SS is formed by five fascicles, divided into three layers: a superficial layer formed by the MdlF and the dorsolateral occipital segment of the ILF; a middle layer formed by the IFOF; and a deep

layer formed by the OR and the AC. The participation of the MdlF, the ILF, and the AC in the formation of the SS was investigated in several studies with different results. Maldonado et al. [19] observed that the MdlF runs within the superficial layer of the SS and interconnects the parietal cortex with the STG. Furthermore, Latini et al. [17] underlined that the ILF occupies the inferior and superficial layer of the SS, while the MdlF is medial and cranial to the ILF. Interestingly, our dissection demonstrated that a small amount of fibers of ILF belongs to the SS and forms the inferior portion of the stratum. The dorsolateral occipital segment [17] of the ILF and the MdlF were contiguous and partially overlapped in our specimens, just medially to the AF-SLF complex (Figs. 2 and 4). The IFOF originates from the frontal lobe and runs in the temporal stem cranial to the UF [32]. Subsequently, it forms the middle layer of the SS running superficially to the OR, on the roof of the temporal horn, directed to the posterior temporal, parietal, and occipital cortex [21].

The lateral extension of the AC passes through the inferior portion of the globus pallidus and medial to the UF, directed to the temporal region [16, 26]. According to our dissections, these fibers join the ventral part of the SS intermingling with fibers of the OR (Fig. 6d). Though we could not distinguish
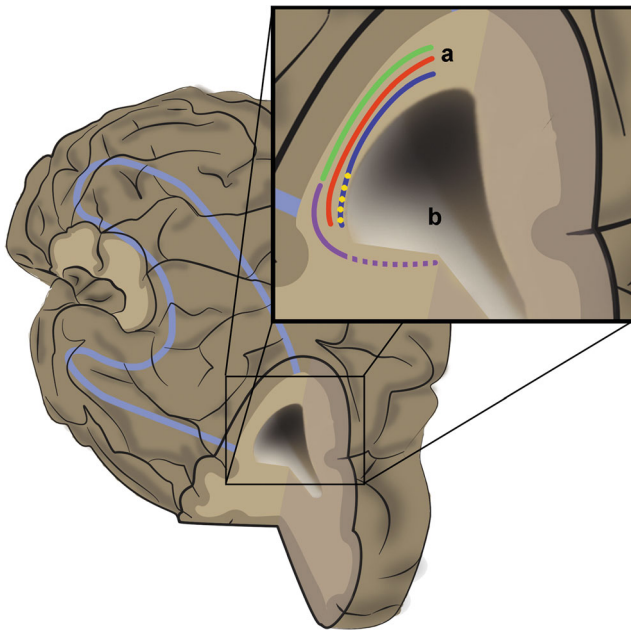
Fig. 8 Schematic representation of the SS (a) at the level of the lateral wall of the atrium (b). The inset shows the three layers of the stratum: the superficial layer is formed by the MdlF (green line), and the dorsolateral occipital portion of the ILF (violet—continue line); the middle layers are formed by the IFOF (red line), and the deep layer is formed by the OR (blue line), intermingled in its inferior part with the AC (yellow spots)

which of these were AC fibers within the SS, it is conceivable that this commissural structure participates in the formation of the deep layer of the SS intermingled with the OR. Accordingly, the main component of the deep layer of the SS is the OR. This fascicle is part of the posterior thalamic peduncle [25], which originates from the lateral geniculate body of the thalamus, **AND** loops posteriorly forming the roof and the lateral wall of the temporal horn. Then it continues laterally to the atrium and superiorly to the occipital horn of the lateral ventricle, and projects to the occipital cortex [9, 25]. Even though several authors focused their study on the deep layer of the stratum [13, 15, 34], our study demonstrated that the more superficial white matter formed by the IFOF, the ILF, and the MdlF contributes to the organization of the periatrial sagittal fibers. Indeed, the results of the lateral dissections are sustained by the coronal cuts (Fig. 7) that give a comprehensive and 3-dimensional view of the SS architecture. It is worth noting that it was not possible to differentiate the fibers of the OR from the projection fibers coming from the occipito-temporal cortex and directed to the pons. The differentiation between internal (corticofugal) and external (corticopetal) fibers evidenced in histological and radiological investigations [13, 15] was not observed in our work. Accordingly, the deep layer of the SS is formed by reciprocal connection between the occipito-temporal cortex, the thalamus, and the brainstem [34, 35, 38], in association to the commissural fibers of the AC.

Although we did not include fiber tractography in our study, its role in the study of white matter anatomy has been clearly established [14]. Even if way beyond the aim of this work, recent DTI-based fiber tractography studies confirmed the results of our dissections. The contiguity of the MdlF and the ILF in a superficial layer of the temporo-parietal white matter was reported in both anatomical and virtual dissection by different groups, sustaining our findings [17, 22]. Furthermore, Peltier et al. in 2011 confirmed the existence of the posterior extension of the AC within the SS with a DTI fiber-tracking analysis [26]. It is noteworthy that the lateral-posterior limb of the AC is challenging to identify with tractography, due to the very small cross-sectional diameter of its fibers [18]. Therefore, even using ultra-high-resolution in vivo diffusion-weighted images (DWI), the overall rate of false bundle could be of concern, and data should be carefully analyzed [18, 36].

Functional anatomy of the sagittal stratum

Several authors focused on the studies of functional implications of the SS on its visual connections [10, 23, 40]. Pandya and colleagues expanded these concepts, suggesting that the SS contains a cortico-subcortical specialized system—the OR—and also projection fibers [34]. They observed reciprocal connections between the parietal and the visual association cortex and the thalamus, as well as connections to the pons, the cerebellum, and the diencephalic and brainstem structures [34]. Accordingly, they hypothesized that damage to the SS could lead to an impairment of higher cognitive functions, in addition to a heterogeneous spectrum of visual deficits [34]. A recent study from Chan-Seng et al. analyzed a series of patients who underwent awake surgery with direct electrical stimulation (DES), for diffuse low-grade gliomas (DLGG) involving the left SS [3]. They observed that subcortical stimulation can induce language semantic disorders, alexia, and visual disturbances [3]. Three main fascicles were functionally detected within the SS: the IFOF, the ILF, and the OR [3]. These observations suggest that the role of the left SS is not limited to visual elaboration. Language impairment, characterized by semantic paraphasia, was noticed stimulating the IFOF, whereas the stimulation of the ILF induced reading impairment and visual agnosia [3]. Furthermore, an increasing body of evidence suggests that the right ILF subserves visuo-spatial processing, and it has a main role in face recognition and visual memory [7, 12]. Similarly, the right IFOF is involved in non-verbal semantic processing and face-based mentalizing [11, 41]. The role of MdlF in cognitive function is still under investigation and it is supposed that it could participate in language-processing [4, 19].

Conclusions

The SS is a neural crossroad situated deep in the lateral aspect of the brain, characterized by a layered structure and involved in language, visual information processing, and cognitive function. This laboratory investigation provides a detailed description of the topographical anatomy of the SS, its layers, limits, and relationship with the surrounding bundles. Applying the detailed knowledge of the white matter tracts to preoperative planning and intraoperative monitoring can assist surgeons to decrease post-operative morbidity.

Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee (University of Pisa) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. The specimens were obtained in the first 12-h postmortem from donors.

References

1. Burdach KF (1826) Karl Friedrich Burdach,...: vom Baue und Leben des Gehirns: Dritter Band. Dyk
2. Catani M, Jones DK, Donato R, Ffytche DH (2003) Occipito-temporal connections in the human brain. Brain. https://doi.org/10.1093/brain/awg203
3. Chan-Seng E, Moritz-Gasser S, Duffau H (2014) Awake mapping for low-grade gliomas involving the left sagittal stratum: anatomofunctional and surgical considerations. J Neurosurg. https://doi.org/10.3171/2014.1.JNS132015
4. DeWitt Hamer PC, Moritz-Gasser S, Gatignol P, Duffau H (2011) Is the human left middle longitudinal fascicle essential for language? A brain electrostimulation study. Hum Brain Mapp. https://doi.org/10.1002/hbm.21082
5. Duffau H, Moritz-Gasser S, Mandonnet E (2014) A re-examination of neural basis of language processing: proposal of a dynamic hodotopical model from data provided by brain stimulation mapping during picture naming. Brain Lang. https://doi.org/10.1016/j.bandl.2013.05.011
6. Ebeling U, Reulen HJ (1988) Neurosurgical topography of the optic radiation in the temporal lobe. Acta Neurochir. https://doi.org/10.1007/BF01401969
7. Fernandez Coello A, Duvaux S, De Benedictis A, Matsuda R, Duffau H (2013) Involvement of the right inferior longitudinal fascicle in visual hemiagnosia: a brain stimulation mapping study. J Neurosurg. https://doi.org/10.3171/2012.10.JNS12527
8. Fernández-Miranda JC, Rhoton AL, Álvarez-Linera J, Kakizawa Y, Choi C, De Oliveira EP (2008) Three-dimensional microsurgical and tractographic anatomy of the white matter of the human brain. Neurosurgery. https://doi.org/10.1227/01.NEU.0000297076.98175.67

9. Goga C, Türe U (2015) The anatomy of Meyer's loop revisited: changing the anatomical paradigm of the temporal loop based on evidence from fiber microdissection. J Neurosurg. https://doi.org/10.3171/2014.12.JNS14281
10. Gratiolet P (1854) Mémoire sur les plis cérébraux de l'homme et des primates. A. Bertrand
11. Herbet G, Moritz-Gasser S, Duffau H (2017) Direct evidence for the contributive role of the right inferior fronto-occipital fasciculus in non-verbal semantic cognition. Brain Struct Funct. https://doi.org/10.1007/s00429-016-1294-x
12. Herbet G, Zemmoura I, Duffau H (2018) Functional anatomy of the inferior longitudinal fasciculus: from historical reports to current hypotheses. Front Neuroanat doi. https://doi.org/10.3389/fnana.2018.00077
13. Hosoya T, Adachi M, Yamaguchi K, Haku T (1998) MRI anatomy of white matter layers around the trigone of the lateral ventricle. Neuroradiology 40(8):477–482
14. Jbabdi S, Sotiropoulos SN, Haber SN, Van Essen DC, Behrens TE (2015) Measuring macroscopic brain connections in vivo. Nat Neurosci. https://doi.org/10.1038/nn.4134
15. Kitajima M, Korogi Y, Takahashi M, Eto K (1996) MR signal intensity of the optic radiation. Am J Neuroradiol 17(7):1379–1383
16. Klingler J, Ludwig E (1956) Atlas cerebri humani. NY Karger, Basel 577:
17. Klingler J, Ludwig E (1956) Atlas cerebri humani. Karger Publishers
18. Maier-Hein KH, Neher PF, Houde J-C et al (2017) The challenge of mapping the human connectome based on diffusion tractography. Nat Commun. https://doi.org/10.1038/s41467-017-01285-x
19. Maldonado IL, De Champfleur NM, Velut S, Destrieux C, Zemmoura I, Duffau H (2013) Evidence of a middle longitudinal fasciculus in the human brain from fiber dissection. J Anat. https://doi.org/10.1111/joa.12055
20. Mandonnet E, Martino J, Sarubbo S, Corrivetti F, Bouazza S, Bresson D, Duffau H, Froelich S (2017) Neuronavigated fiber dissection with pial preservation: laboratory model to simulate opercular approaches to insular tumors. World Neurosurg. https://doi.org/10.1016/j.wneu.2016.10.020
21. Martino J, Brogna C, Robles SG, Vergani F, Duffau H (2010) Anatomic dissection of the inferior fronto-occipital fasciculus revisited in the lights of brain stimulation data. Cortex. https://doi.org/10.1016/j.cortex.2009.07.015
22. Martino J, da Silva-Freitas R, Caballero H, Marco de Lucas E, García-Porrero JA, Vázquez-Barquero A (2012) Fiber dissection and diffusion tensor imaging tractography study of the temporoparietal fiber intersection area. Oper Neurosurg. https://doi.org/10.1227/NEU.0b013e318274294b
23. Meyer A (1907) The connections of the occipital lobes and the present status of the cerebral visual affections. Trans Assoc Am Phys 22:7–16
24. Mori S, Oishi K, Jiang H et al (2008) Stereotaxic white matter atlas based on diffusion tensor imaging in an ICBM template. Neuroimage. https://doi.org/10.1016/j.neuroimage.2007.12.035
25. Párraga RG, Ribas GC, Welling LC, Alves RV, De Oliveira E (2012) Microsurgical anatomy of the optic radiation and related fibers in 3-dimensional images. Neurosurgery. https://doi.org/10.1227/NEU.0b013e3182556fde
26. Peltier J, Verclytte S, Delmaire C, Pruvo JP, Havet E, Le Gars D (2011) Microsurgical anatomy of the anterior commissure: correlations with diffusion tensor imaging fiber tracking and clinical relevance. Neurosurgery. https://doi.org/10.1227/NEU.0b013e31821bc822
27. Pescatori L, Tropeano MP, Manfreda A, Delfini R, Santoro A (2017) Three-dimensional anatomy of the white matter fibers of the temporal lobe: surgical implications. World Neurosurg. https://doi.org/10.1016/j.wneu.2016.12.120

28. Peuskens D, Van Loon J, Van Calenbergh F, Van Den Berg R, Goffin J, Plets C (2004) Anatomy of the anterior temporal lobe and the frontotemporal region demonstrated by fiber dissection. Neurosurgery. https://doi.org/10.1227/01.NEU.0000140843.62311.24

29. Polyak S (1957) The vertebrate visual system: its origin, structure, and function and its manifestations in disease with an analysis of its role in the life of animals and in the origin of man; preceded by a historical review of investigations of the eye, and of the visu. University of Chicago Press, Chicago

30. Putnam TJ (1926) Studies on the central visual connections: III. the general relationships between the external geniculate body, optic radiation and visual cortex in man: report of two cases. Arch Neurol Psychiatr. https://doi.org/10.1001/archneurpsyc.1926.02200290029003

31. Reil JC (1809) Das hirnschenkel-system oder die hirnschenkel-organisation im großen gehirn. Arch für die Physiol 9:147–171

32. Ribas EC, Yagmurlu K, Wen HT, Rhoton AL (2015) Microsurgical anatomy of the inferior limiting insular sulcus and the temporal stem. J Neurosurg. https://doi.org/10.3171/2014.10.JNS141194

33. Sachs H (1892) Das Hemisphärenmark des menschlichen Grosshirns: Der Hinterhauptlappen/von Heinrich Sachs. Thieme

34. Sachs DH (1892) Das Hemisphärenmark des menschlichen Grosshirns. 1. Der Hinterhauptlappen, von Dr. med. Heinrich Sachs,... Mit einem Vorwort von... C. Wernicke... G. Thieme

35. Schmahmann J, Pandya D (2009) Fiber pathways of the brain. OUP USA

36. Thomas C, Ye FQ, Irfanoglu MO, Modi P, Saleem KS, Leopold DA, Pierpaoli C (2014) Anatomical accuracy of brain connections derived from diffusion MRI tractography is inherently limited. Proc Natl Acad Sci U S A. https://doi.org/10.1073/pnas.1405672111

37. Türe U, Yaşargil DCH, Al-Mefty O, Yaşargil MG (1999) Topographic anatomy of the insular region. J Neurosurg. https://doi.org/10.3171/jns.1999.90.4.0720

38. Türe U, Yaşargil MG, Friedman AH, Al-Mefty O (2000) Fiber dissection technique: lateral aspect of the brain. Neurosurgery. https://doi.org/10.1097/00006123-200008000-00028

39. Tusa RJ, Ungerleider LG (1985) The inferior longitudinal fasciculus: a reexamination in humans and monkeys. Ann Neurol. https://doi.org/10.1002/ana.410180512

40. von Flechsig P (1896) Weitere mitteilungen über den stabkranz des menschlichen grosshirns. Neurol Cent 15:2–4

41. Yordanova YN, Duffau H, Herbet G (2017) Neural pathways subserving face-based mentalizing. Brain Struct Funct. https://doi.org/10.1007/s00429-017-1388-0