Anatomy of Important Functioning Cortex

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Core Messages

- Important functioning cortex includes the language areas (Anterior, Posterior, and Superior), primary sensorimotor, and primary visual cortex.
- Specific white matter pathways (e.g. arcuate fasciculus, corticospinal tract, geniculocalcarine tract) are of equal importance to preserve in order to avoid compromise of critical neurological function.
- Neuronavigation greatly facilitates the recognition of gyral and sulcal patterns that can reliably identify many important functional zones as well as defining landmarks that demarcate the boundaries of regions of eloquent cortex.
- The cortex is composed of gyral folds that are connected through pli de passage. These folds connect adjacent gyri and adjacent lobes forming continuous ribbons of cortex containing a white matter core.
- The technique of subpial/endopial resection must be applied whenever preservation of bypassing vessels is critical to avoid ischemic injury to critical functioning cortex.

Introduction

Important functioning cortex describes all the cortical brain regions that subserve discreet and critical function. Although presumably all cortical areas are capable of being engaged in useful function, some brain regions are clearly more critical to human function than others. This chapter deals with such highly critical areas of the brain that are discreet and can be defined anatomically. The classical language areas, sensorimotor cortex, and vision cortex are discussed in addition to correlative sulcal and gyral anatomy.

In general, cortical regions outside important functioning cortex are considered "safe" to resect. But there are important safety considerations of surgery outside areas of critical functional. First, beneath the cortex are white matter pathways that may be as critical to important function as the cortex itself because of the synaptic

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impulses the fibers are conveying. Second, as already alluded to, areas of cortex that do not accommodate important functioning cortex, may still engage in useful cognitive activities that would result in some degree of functional decline if resected or disconnected, an example is a frontal lobe resection that preserves Broca's area and its connections. Practically, however, the disease conditions we treat that may require a lobar resection, such as epilepsy or brain tumor, would be expected to enhance function and not detract from function if the intractable frontal lobe epilepsy focus is removed resulting in seizure freedom, or the large frontal brain tumor causing mass effect that is impairing cognitive function is resected and decompressed. Third, the vascular territory, both arteries and veins, are of critical concern when operating in or near to important functioning cortex. The arteries passing through or around a safe resection site may be irrigating critical areas distant from the resection and veins may be draining similar critical cerebral regions. In both situations, the vessels must be preserved to prevent ischemia or stroke and interference with function. The surgical strategy to protect bypassing vessels including the sulci in which vessels are coursing is called subpial gyral emptying, which will be discussed in this chapter.

The term eloquent is often used to describe all critical brain regions. However, this word is troublesome when describing sensorimotor function, for example, because the meaning of eloquent is to be fluent or persuasive in speaking, such as an eloquent speech. Eloquent takes its origin from Old French and Latin and has the same roots as loquacious (tending to talk a great deal; talkative). Therefore, this chapter will avoid the word eloquent unless referring strictly to language function.

Topographic Brain Mapping

Neuronavigation has remarkably facilitated the process of cerebral localization [1]. Structures that are known for their specific functions such as the precentral gyrus can be readily identified and localized on the cortical surface based on the gyral and sulcal morphology. Such critical information nowadays rapidly and reliably available can make awake craniotomy and brain stimulation mapping unnecessary when a resectable lesion is located at a safe distance from such a functional area. For surgery performed within and very near to important functioning cortex, local anesthesia with cortical stimulation remains an important technique to confirm the safety of a resection. The value of neuronavigation in this case is as a guide to make the stimulation procedure more efficient by showing the surgeon where to begin the stimulation process based on anatomical localization of function. In both cases of awake surgery and under general anesthesia, neuronavigation has become an essential tool to define the location and extent of a lesion as well as to confirm normal anatomy.

It is possible with 3D reconstruction imaging to obtain a vivid representation of the gyral and sulcal pattern of the cortex (Figs. 3, 5, 6, 10, 12). The three dimensional aspects of the surgical anatomy are best appreciated by creating a volumetric reconstruction in the neuronavigation environment. For example, the central sulcus and the pre and postcentral gyri can be readily identified with imaging. Even specific function such as hand sensory and motor, tongue, lips, and face areas can be reliably identified by unique gyral patterns, which facilitates the process of cortical stimulation when needed. Many of the cerebral gyri have a typical configuration and pattern with folds and passages called pli de passage that continue into adjacent gyri that can be identified with neuronavigation. Nowadays there are a myriad of platforms and software available that can construct brain maps incorporating important structures or a lesion by segmentation of the 3D volume. In addition, these reconstructed images are invaluable learning and teaching tools, for the medical staff, patients, and their families.

Gyral Continuum

The arrival of MRI 3D reconstruction has revived the old textbooks of anatomy that had been waiting for a new opportunity to reveal the enormous, precise, and practical information on cortical topography usually illustrated with high artistic value. Textbooks of the old French school of

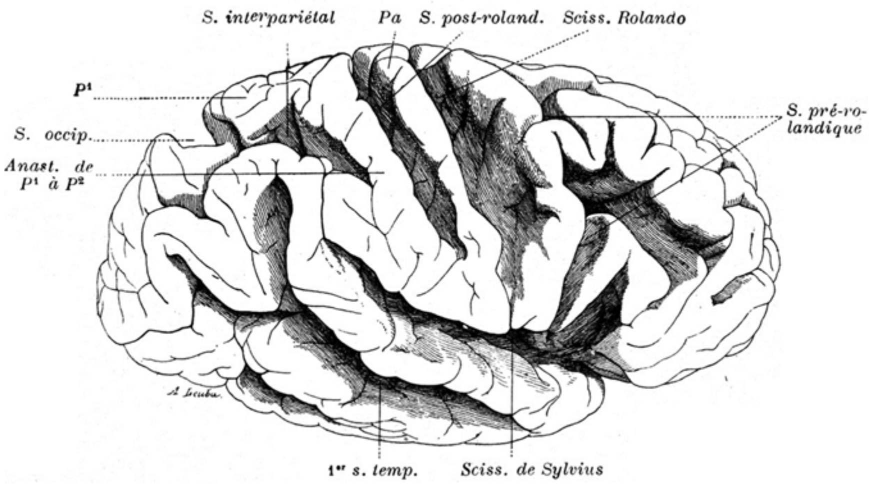

Fig. 1 Display of gyral–sulcal anatomy. The width of sulci is exaggerated to better display the concept of gyral continuum. Reprinted from: Poirier et Charpy. *Anatomie humaine*, Paris, Masson, 1921

anatomy are excellent examples and particularly one from Poirier and Charpy published in 1921 [2] (Fig. 1). The crisp MRI 3D reconstructions display with astonishing clarity the early tedious observations made on the cadaver brain with special emphasis on the gyral and sulcal anatomy. The concept of gyral continuum is not new having been described in detail by Paul Broca [3], which he called "plis de passage," a reference to anatomical bridges joining one gyrus to another or the transition of one gyrus into another. What is new is its application to microsurgical techniques and in particular to the endopial resection technique [1]. A "pli de passage" refers to an anatomical bridge or continuum between two gyral structures bearing different names (Figs. 1, 2, 3, 4, 5, and 6). The anastomotic bridges of the plis de passage reveal the cortical continuum over the more superficial aspect of the brain. However, it is important to keep in mind the continuum around the sulci that could be described as the sulcal continuum, which is formed by the cortex applied against the pia on one side of a sulcus continuous at the bottom of the sulcus with the cortex on the opposite side that is part of a different gyrus or lobe. It is with this gyral cortical continuum in mind that a practical gyral terminology concept was developed by the old French anatomists that uses numbers

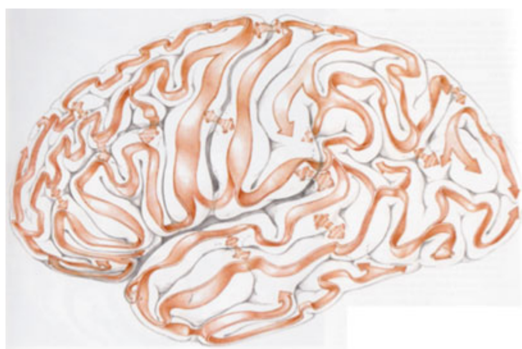

Fig. 2 Gyral continuum. F1, F2, and F3 are continuous with the precentral gyrus via gyral continuum. The postcentral gyrus is continuous superiorly with the superior parietal lobule (P1) and inferiorly with supramarginal gyrus (P2 or inferior parietal lobule). Yasargil et al. described the concept as gyral ribbons. MG Yasargil. Thieme Medical Publishers, 1994, New York, p.24, courtesy of Georg Thieme Verlag KG.

and letters. Thus within the frontal lobe the continuum gives rise to F1, F2, and F3 gyri (superior, middle, and inferior frontal gyri, respectively, along with contributions to the mesial and orbital surfaces.) (Figs. 1, 2, 3, 4, 10, 15). Within the temporal lobe we find in a superolateral to inferomesial sequence a similar circular pattern around the lobe of T1, T2, T3, T4, T5, T6, and T7 (Figs. 3, 4, 5, and 6). In the occipital lobe the gyral sequence is O1, O2, O3, O4, O5, and O6

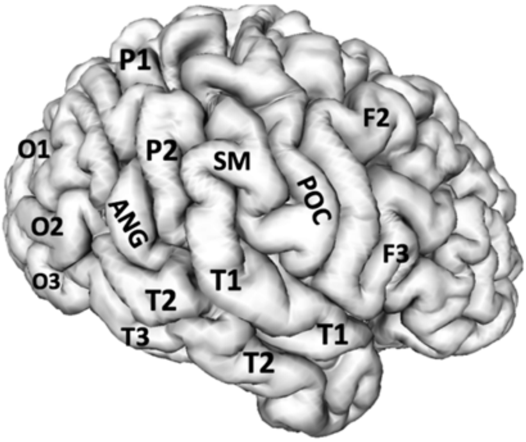

Fig. 3 3D MRI reconstruction. F2 and F3 are seen to take root from and are continuous with the precentral gyrus. The postcentral gyrus is continuous superiorly with the superior parietal lobule (P1) and inferiorly with the supramarginal gyrus (P2 or inferior parietal lobule). In this individual, the superior pli of the postcentral gyrus with P1 is more inferiorly located than is typical. P1 becomes O1. T1 can be identified merging with the supramarginal gyrus. T2 contributes both to the angular gyrus and O2. T3 continues posteriorly to become O3. *ANG* angular gyrus, *SM* supramarginal gyrus, *POC* postcentral gyrus

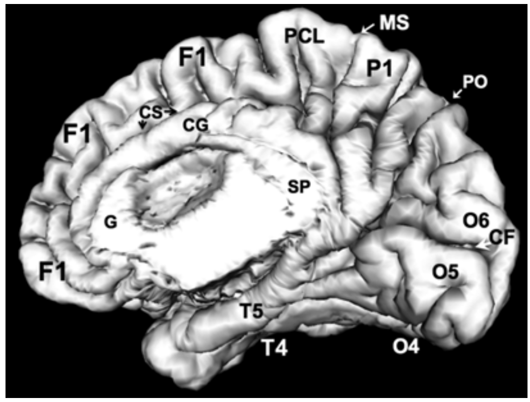

Fig. 5 Mesial cortical surface. T5 (parahippocampal gyrus) is split posteriorly by the anterior limb of the calcarine fissure to become superiorly the isthmus of the cingulate gyrus (CG) and inferiorly the lingual gyrus (O5). The cuneus (O6) and lingual gyrus (O5) are separated by the posterior limb of the calcarine fissure (CF). The cingulate sulcus (CS) separates F1 (first frontal gyrus) from the cingulate gyrus (CG). *PO* parieto-occipital fissure, *O4* lateral occipital gyrus anteriorly is named T4 (fusiform gyrus), *MS* marginal sulcus

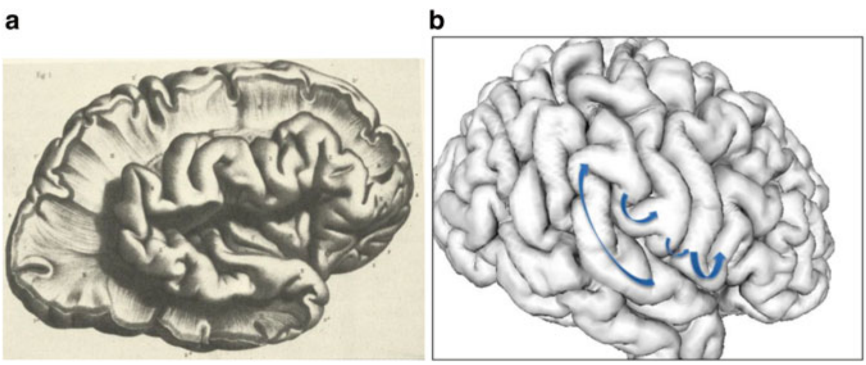

Fig. 4 (**a**) The encircling gyrus of Foville. *circonvolution d'enceinte* (Foville 1844). (**b**) To illustrate the gyral continuum concept, one cortical ribbon winds around the sylvian fissure but with different named parts. The first temporal gyrus extends into the posterior limb of the supramarginal gyrus. The anterior limb is continuous with the postcentral gyrus. The precentral and postcentral gyri connect via the subcentral gyrus and F3 originates as a continuum from the inferior precentral gyrus

(Figs. 3, 4, 5, and 6). The parietal lobe is divided into P1 and P2 (Figs. 3, 17, 18). Knowledge of the gyral and sulcal continuum is of practical importance during cortical resections. For example, when resecting a lesion posteriorly in F2, there is no pial boundary to prevent the surgeon from entering the precentral gyrus. These two gyri of different names are in fact a continuous cortical and white matter ribbon (Fig. 2). Although the overall patterns of gyral continuum are constant, they nevertheless vary with each patient and must be recognized as such.

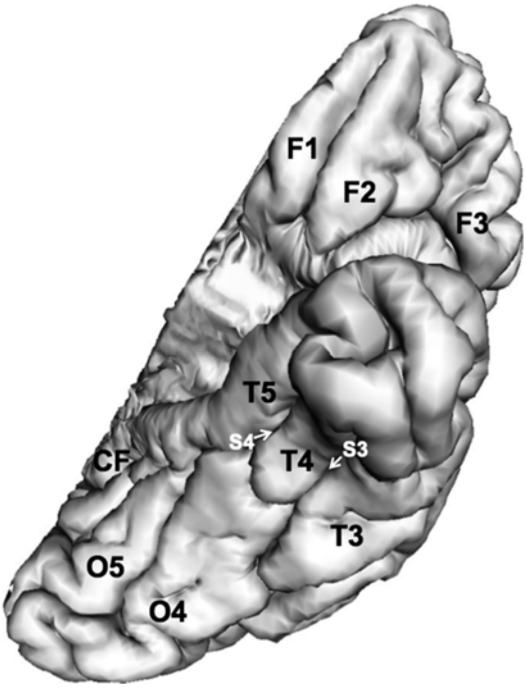

Fig. 6 Inferior surface of the hemisphere. See text for label identification

The Gyral Continuum over the Lateral Convexity

The three frontal transverse gyri (F1, F2, and F3) are continuous with the precentral gyrus through three plis de passage that of F1 and F2 being conspicuous and that of F3 often hidden within the sylvian fissure (Figs. 2, 3, 10, 15). The gyral continuum that forms the perisylvian area is impressive (Fig. 4). It is in fact a single gyrus surrounding the three sides of the sylvian fissure but named for its constituent parts. The first temporal gyrus (T1) continues into the posterior limb of the supramarginal gyrus then through its anterior limb the supramarginal gyrus caps the posterior ascending limb of the sylvian fissure. This feature is useful to recognize the position of the central sulcus and surrounding structures. From the supramarginal gyrus, the continuum extends forward through anatomical bridges into the lower postcentral gyrus, then precentral gyrus, and finally into the third frontal gyrus (F3).

The superior parietal lobule (P1) blends with the upper part of the postcentral gyrus through an anastomic bridge, and the supramarginal gyrus part of P2 is continuous inferiorly with the postcentral gyrus. There is variation in the structure of P2, but the typical gyral pattern consists of a posterior limb of the supramarginal gyrus merging with the anterior limb of the angular gyrus whose posterior limb is a continuation of the posterior superior extension of T2 (Figs. 3, 4, 17). The superior parietal lobule (P1) will merge with the first occipital gyrus (O1), the inferior parietal lobule (P2) along with T2 merges with the second occipital gyrus (O2), and T3 continues posteriorly to become O3 (Figs. 3, 5, 6).

The Gyral Continuum over the Mesial Surface (Fig. 5)

T4 (fusiform gyrus) extends from the temporal pole and blends with O4 that reaches the occipital pole. T5 (parahippocampal gyrus) does not reach the temporal pole but rather bends on itself to form the hippocampal lobule (piriform lobe). The reflected inner component of the lobule is the uncus. The limbic (rhinal) sulcus separates the hippocampal lobule from the temporal pole. The parahippocampus (T5) is separated posteriorly by the proximal calcarine fissure (CF) and is continuous with the lingual gyrus (O5) inferiorly and via the isthmus with the cingulate gyrus superiorly. The mesial part of the superior parietal lobule (P1) corresponds to the precuneus. It is separated from the cingulate gyrus by a remnant of the cingulate sulcus, the subparietal sulcus. The mesial central area forms the paracentral lobule that is a fusion of the precentral and postcentral gyri. Figure 5 shows a strong pli de passage between the precentral gyrus and the posterior mesial portion of F1. The paracentral lobule is limited inferiorly by the cingulate sulcus.

Most of the mesial frontal area is occupied by the interhemispheric part of F1. The cingulate gyrus forms the remainder of the mesial cerebral cortex in the frontal area. It surrounds the corpus callosum from which it is well separated by the deep callosal sulcus. The upper border of the cingulate gyrus is the cingulate sulcus that extends posteriorly behind the paracentral lobule as the marginal sulcus. Note also how the subcallosal portion of the cingulate gyrus blends with F1. Broca called this junctional zone the “carefour de l’hémisphère.”

The Gyral Continuum over the Inferior Surface (Fig. 6)

On the ventral brain surface, the most conspicuous structure is the fourth temporal gyrus (T4), which posteriorly becomes the fourth occipital gyrus (O4). It is well demarcated medially by the deep collateral sulcus (S4) and laterally by the S3 sulcus that is shallow and filled by many anastomotic bridges between T3 and T4. The parahippocampal gyrus (T5) is divided by the anterior calcarine fissure (CF). Upwards it becomes the isthmus that blends with the cingulate gyrus and inferiorly through the temporo-occipital isthmus becomes the lingual gyrus (O5).

The gyrus rectus (F1) is the inferior continuation of the F1 frontal gyrus. Its lateral border is the mesial orbital sulcus. Between the mesial and lateral orbital gyri is the H gyrus that is the inferior extension of F2. Lateral to the lateral orbital sulcus is the anterior-inferior extension of F3 gyrus, called the pars orbitalis.

Summary for the Clinician

- The gyral continuum are folds of cortex and white matter connecting adjacent gyri and lobes of the brain.
- There are no arachnoid-pial or sulcal boundaries separating gyri that are connected through pli de passage.
- The naming system for gyri using numbers and letters is useful because it describes the actual cortical anatomy which is gyral ribbons that flow through continuum or pli de passage between lobes and adjacent gyri.

Endopial Resection (Intervascular Endopial Gyral Emptying)

The endopial resection describes a surgical technique defined by the selective removal of tissue while leaving in situ the pia-arachnoid sulci that envelopes the vasculature (Fig. 7). In the case of epilepsy, for example, the supportive sulci and vascular elements do not require resection since they do not participate directly in the seizure process. Frequently at surgery a scenario is encountered in which interference of bypassing blood vessels found in close proximity to important functioning areas will risk postoperative deficits. In these cases, the goal is to maintain the vascular supply to critical tissues or areas and thus preserve the integrity of the regional vascular territory. In surgery for intrinsic brain tumor, there is in most cases preservation of the pial boundaries with filling and expansion of the involved gyri by the tumor thus facilitating preservation of the vasculature. In fact, neurological complications

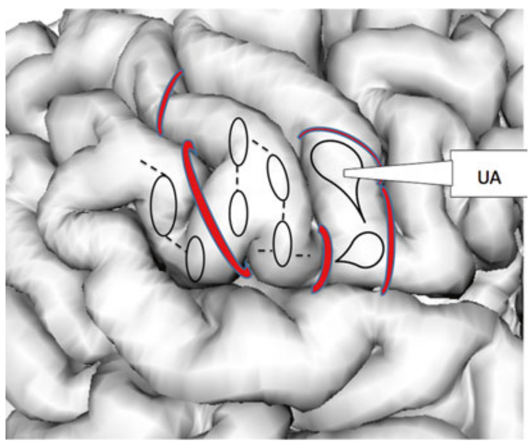

Fig. 7 Lower central area and anterior limb of supramarginal gyrus resection, an example of endopial intervascular emptying. The ultrasonic aspirator (UA) is the ideal tool used at low settings of aspiration and amplitude. Small openings are made in the pia over the gyral surface in order to introduce the suction tip to start the subpial and endopial removal of tissue. The pial openings are enlarged by coagulating and dividing the pia with microscissors (*dashed lines*) while preserving bypassing vessels and adjacent sulci. The pial layers of the sulci, overlying cisterns and Sylvian fissure, in this case, are all kept intact. Ultimately, the desired gyrus or gyri are emptied in a subpial fashion in order to treat the condition as well as preserve function

of surgery are either due to the actual resection of functional tissue or to the secondary damage to functional areas resulting from the occlusion or injury to critical blood vessels.

The alternative resection technique is en bloc, which entails coagulating and dividing blood vessels that terminate within or traverse the resected area. A lobe or a region of the brain is then removed leaving behind a large cavity. The classical examples of en bloc technique are temporal lobectomy and frontal polar resection where the actual removal entails the division of opercular arteries and, at times, of veins running over the cortex. There are usually no side effects or complications since the resection is restricted to a rather silent area and because potential swelling from coagulating and dividing vessels is compensated by a relatively large removal cavity. However, there are many instances where an en bloc resection cannot be carried out due to risk of causing infarction in a more distal vascular territory.

The locations most appropriate for the intervascular endopial emptying technique are within or nearby important functioning cortical areas, and where an appraisal of the vascular anatomy demonstrates a risk of infarct from vessel occlusion. The technique of subpial dissection is not new. It was originally described by Horsley [4], and is well known to neurosurgeons particularly in the field of epilepsy surgery where it has been used routinely. However, the systematic use of endopial emptying, skeletonization, and preservation of blood vessels for removal of epileptogenic and brain tumor tissue is a newer and original concept [1].

Many of the standard resective procedures, such as the anterior temporal resection for epilepsy, consist of a combination of en bloc resection and endopial emptying. At times, however, the entire procedure is carried out through multiple openings through the arachnoid and the pia to empty one or more gyri subpially. Surgery in the inferior central area is always performed using the intervascular endopial gyral emptying technique if the goal is to preserve function in the primary sensorimotor area (Figs. 7 and 8). The technique entails coagulation of the pia that is perforated with the tip of a sharp bipolar working between the blood vessels that are to be preserved. The ultrasonic aspirator has in our hands been the ideal tool to use set at lowest parameters of aspiration and amplitude. In comparison, a regular suction tip tends to create more trauma and bleeding. The ultrasonic aspirator is introduced into the pial openings, to aspirate gyral contents creating small cavities that are extended along by subpial aspiration. The pia covering the gyral core of the resec-

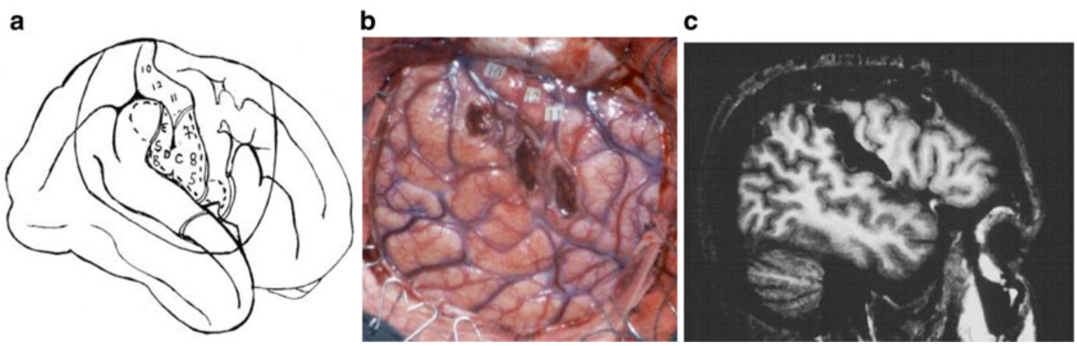

Fig. 8 Case of intractable epilepsy with a focus in the inferior central area and supramarginal gyrus. The resection approach illustrates the intervascular endopial gyral emptying technique. (**a**) Operative diagram showing responses to stimulation and *dotted line* encompassing the resection performed in a subpial endopial fashion. (**b**) Endopial intervascular emptying has been started in the anterior limb of the right supramarginal gyrus. The pia below tag #11 has been coagulated and will be opened to allow the lower postcentral gyrus to be emptied preserving the bypassing arteries. (**c**) Postoperative sagittal MRI showing the extent of resection. The parietocentral resection included the anterior limb of supramarginal gyrus, inferior postcentral gyrus, and a small opercular portion of the precentral gyrus. The pia-arachnoid of the sulci and Sylvian fissure were kept intact as were bypassing arteries and veins

tion line is opened with micro scissors up to the neighboring blood vessels that are preserved. These cavities are joined together by dissecting between, under, and around the by-passing blood vessels (Figs. 7 and 8). The adjacent sulci that are the pial boundaries with their intrinsic vessels are recognized and left intact after the white matter and adherent cortex or brain tumor is removed in a subpial fashion. A dry surgical field is maintained by suction on a micro sponge, irrigation, and gelfoam if needed. Coagulation is used for the initial pial opening, and is not necessary for the endopial emptying of the gyrus.

For a resection in the lower central area, intervascular endopial gyral emptying is the appropriate resection technique. The inferior central anastomotic bridge (pli de passage) that connects the pre and postcentral gyrus is identified and entered (Figs. 7 and 8). The middle cerebral artery vessels (pre-central, central, and postcentral arteries) as well as draining veins are preserved. The sulci and pia arachnoid covering the Sylvian fissure is preserved. The resection is carried out through several pial openings and cavities that are progressively enlarged and joined together. The contents of the peri-Sylvian gyri can be emptied in a subpial fashion down to the insula leaving undisturbed, the M2, M3, and M4 segments of the middle cerebral artery. Multiple cavities of subpial aspirated tissue is accomplished between traversing vessels and intervening sulci; postoperative imaging makes apparent the full extent of the resection (Fig. 8).

In parasagittal frontal and parietal resections, the intervascular endopial gyral emptying approach is useful when large draining veins that are desirable to be preserved cross the area to be resected. For example the vein of Trolard draining the central area. In the dominant hemisphere it is essential to prevent interruption of vessels that supply or drain eloquent cortex. In a resection limited to the first frontal gyrus, the looping marginal branches of the anterior cerebral artery are left intact as well as significant ascending veins to prevent infarction of large areas of unresected cortex. The F1 subpial dissection can be carried out along the mesial surface pia down to the cingulate sulcus, and if the cingulate gyrus is to be removed, subpial resection is carried out around the depth of the sulcus in order to empty the cingulate gyrus proper. In this example, all intrasulcal arteries are left intact along with their enveloping pia.

Summary for the Clinician

- Important vessels that irrigate or drain distant cortical regions must be preserved to avoid ischemic injury.
- For surgery within or very near to important functioning cortex, the subpial endopial technique is required to preserve vasculature supplying areas of critical function.

The Central Area (Primary Sensorimotor Area)

Neuronavigation has nowadays made routine the identification of the central sulcus during surgery. It becomes relatively easy to visually recognize the lower extent of the central sulcus including its vascular anatomy on the navigation MRI. Likewise, the vascular anatomy of the inferior central area is unique with a central artery that takes a characteristic path as it exits from the sylvian fissure, loops over the rolandic operculum then dives early and deep into the lowermost part of the central sulcus (Fig. 7). Pre- and postcentral arteries enter a sulcus at a more superior level as well as often sending a branch or directly entering the central sulcus. Not only has neuronavigation proven useful in identifying the central sulcus anatomically, certain clear anatomical landmarks can be readily identified that are useful guides specific to sensory and motor functions [5–9].

Identification of the sensorimotor area (pre- and postcentral gyrus) is frequently required in order to perform resections for brain tumor and epilepsy. Identification of the tongue is the best starting point to map the sensorimotor area, and by extension the whole central area. Figure 9 represents the somatotopic sensory organization

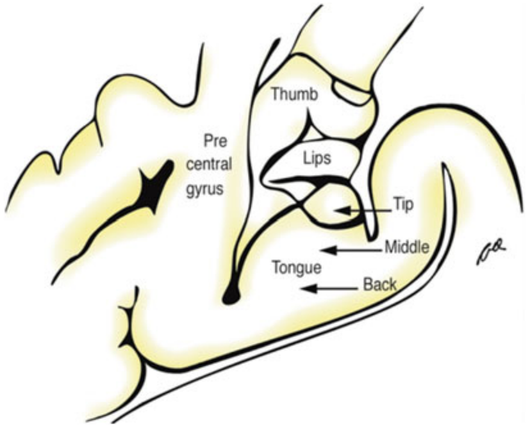

Fig. 9 Somatotopic organization of the lower postcentral gyrus showing sensory representation of tongue, lips, and thumb

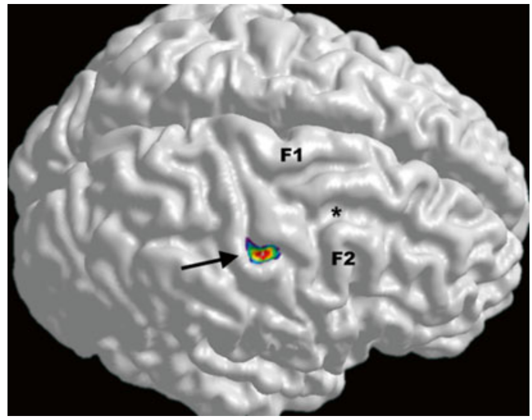

Fig. 10 3D reconstruction of the cortical surface with hand area activation (*arrow*) within the central sulcus. The hand activation is within a posterior pointing curve of the central sulcus that Broca described as the middle bend. The hand sensory and motor areas have a constant relationship with the posterior extent of the superior frontal sulcus (*asterisk*), between the gyral continuum of F1 and F2 with the precentral gyrus

of the lower postcentral area. The base or back of the tongue is represented along the sylvian fissure, and the tip of the tongue about 2.5 cm above the sylvian fissure, adjacent to the lips area [1, 9]. The sensory and motor areas are roughly mirror images of the functional zones representing the same body parts divided by the central sulcus.

Stimulation of the postcentral gyrus typically yields sensory phenomena that are described by patients as a feeling of numbness, tingling, or electricity. The removal of a part of the postcentral gyrus results in decreased two-point discrimination and a loss of proprioception in the body part represented. In the inferior postcentral gyrus, removal of tongue, and face areas has little clinical consequence due to the fact that there is considerable bilateral representation. However, disturbance of the more superior thumb, finger, and hand areas in the postcentral gyrus can result in significant impairment of proprioception. Removal of foot area will make ambulation difficult due to loss of foot propioception.

Stimulation of the precentral gyrus results in contraction of muscle groups in elementary flexion or extension movements of a contralateral limb or part of a limb, or simple movement of the tongue or face. Removal of the precentral gyrus causes paresis but not paralysis. The motor deficit is most profound in the distal extremity, so that the arm may have antigravity strength at the shoulder, but the hand will not have useful function. No significant deficits are expected from removal of the inferior precentral gyrus subserving face and tongue functions due to bilateral cortical representation, although, an asymmetry in the nasolabial fold is often detected after face area resection.

Identification of the lower central area has been a crucial landmark for some time. Penfield described the central and precentral sulci as guides to the posterior extent of temporal lobe resection along T1, identified with cortical stimulation. Neuronavigation nowadays is able to confirm the unique gyral pattern of the ascending pre- and postcentral gyri recognized on the MRI.

The central sulcus is the most constant sulcal landmark on the surface of the human brain. Its inferior point originates just above the sylvian fissure and reliably at the level of a plane drawn at the midpoint of the corpus callosum [10]. The central sulcus takes a sinusoidal shape with three dominant curves. The early French anatomists such as Broca and Dejerine, described a genou superieur and a genou inferieur of the central sulcus, both convex anteriorly, and a genou moyen (middle bend) convex posteriorly. The middle bend has constant anatomical relationships, lying between the gyral continuum insertion of F2 and F1 (Fig. 10). This bend is the surface landmark identifying the pli de passage moyen or hand motor and sensory area in the pre- and postcentral gyri [5, 6, 8]. The central sulcus curves superiorly and posteriorly to end at the interhemispheric fissure in the paracentral lobule, which is found just anterior to the ascending limb of the cingulate sulcus (marginal sulcus) and posterior to the mid callosal plane (Fig. 13). Somatotopic organization maps of motor and sensory localization using cortical stimulation, evoked potentials, and functional imaging are in agreement that a somatotopic relationship exists for the representation of motor and sensory functions extending from the cingulate sulcus, on the mesial surface of the brain, to the sylvian fissure (Figs. 9, 10, 12). The sensory and motor areas are roughly mirror images of the functional zones representing the same body parts divided by the central sulcus.

High-quality MRI and neuronavigation permit routine localization of cortical function in the central area by unique gyral and sulcal anatomic patterns. The presence of a pli de passage (or knob on axial slice imaging) in the middle bend of the precentral gyrus is highly correlated with hand motor and sensory function [5, 6, 8] (Figs. 10 and 11). Additionally, the tongue sensory region is identified with cortical stimulation in a unique triangle-shaped gyral structure at the base of the postcentral gyrus (Figs. 9 and 12) [9]. Back of the tongue sensation occupies the wide, inferior base of the postcentral gyrus, which narrows superiorly to tip of the tongue, then superiorly lower face followed by thumb sensory areas [7].

Seemingly incongruous with hand motor and sensory function located in a relatively small distinct cortical fold, the pli de passage moyen, is the extensive documentation of a somatotopic representation of individual fingers and thumb along the pre- and postcentral gyri that extends along a much longer expanse of the cortex of the central area, over half or more of the precentral gyrus on the lateral convexity according to many stimula-

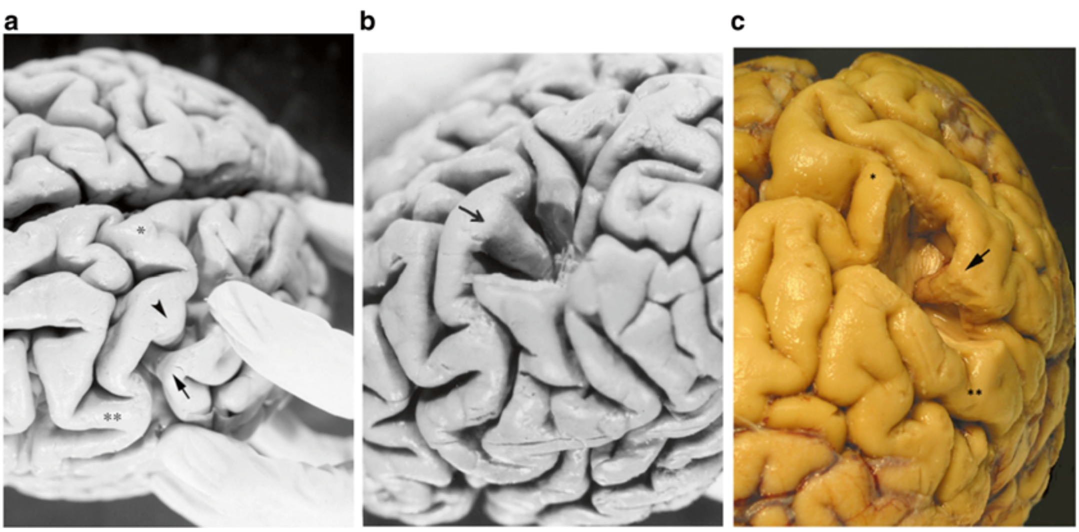

Fig. 11 Three gyral continuum (pli de passage) connect the pre- and postcentral gyri. At the interhemispheric fissure is the pli de passage superior. Just above the sylvian fissure and at times operculated is the pli de passage inferior (subcentral gyrus). At the level of the middle bend of the central sulcus the middle pli is found mostly hidden within the central sulcus. This pli de passage moyen is the cortical representation of whole hand motor and sensory function. (**a**) Broca described this cortical fold as connecting the pre- and postcentral gyri and elevating the floor of the central sulcus. It is constantly located at the posterior termination of the superior frontal sulcus. *Arrowhead* points to the precentral hand motor area, which is the dominant of the two pli. *Arrow* points to the postcentral pli de passage moyen that is the hand sensory area. (**b**) Postcentral gyrus hand area has been cut away to illustrate the precentral hand motor area bulging into the central sulcus (*arrow*). (**c**) Precentral gyrus cut away between the F1 gyral continuum (*asterisk*) and the F2 gyral continuum (*double asterisk*). *Arrow* is pointing to the postcentral gyrus pli de passage moyen that is the sensory hand area

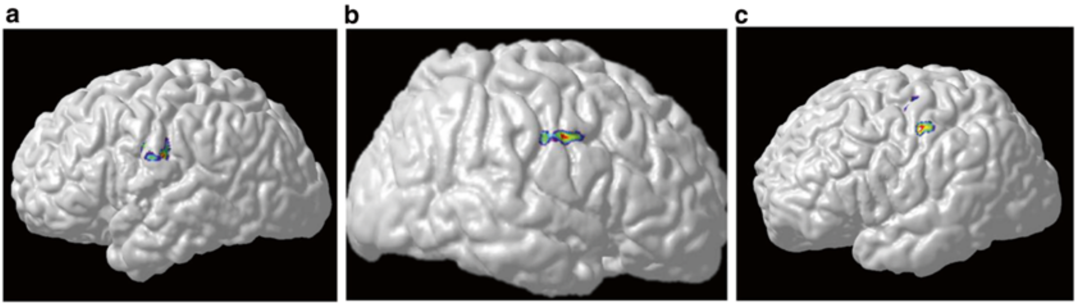

Fig. 12 Sensory H_2O^{15} PET activation studies demonstrate characteristic functional localization based on gyral morphology. (**a**) Anterior tongue sensory activation is found in the triangle-shaped tongue sensory area of the postcentral gyrus. (**b**) Lower face and lips sensory activation is within a narrowed part of the postcentral gyrus just above the tongue area. (**c**) Thumb sensory activation is the most inferior somatotopically represented digit sitting just above the lips and face area. Compare with Fig. 9

tion studies [11]. Therefore, a whole-hand motor and sensory region in the central area would imply function redundant to individual finger somatotopy. Moreover, central area function identified with cortical stimulation does not typically yield complex or coordinated movements. For these reasons, the actual functional role of the pli de passage moyen until recently has not been clearly understood. In fact, hand motor and sensory activation within the pli de passage moyen mat be an artifact of functional imaging that is not able to resolve activation of individual finger somatotopy. However, a whole hand motor and sensory functional area at the anatomical pli de passage moyen has been confirmed with cortical stimulation [5] in addition to individual finger and thumb function found more inferiorly along the precentral and postcentral gyri. The whole hand motor responses are flexion or extension movements obtained with stimulation over the precentral gyrus contribution to the pli de passage moyen. Sensory responses from stimulating the postcentral part of the pli de passage moyen are described by patients as a sensation involving the entire hand. Inferior to the whole hand sensory and motor areas resides individual finger and thumb somatopic sensory and motor functional representation.

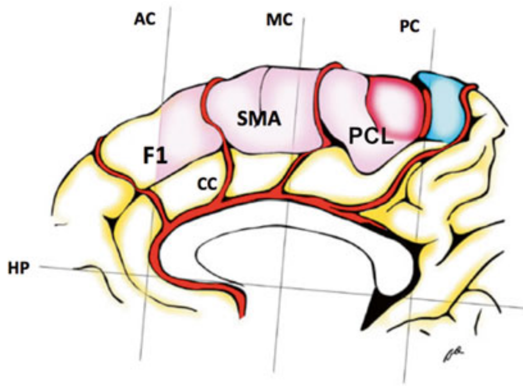

Fig. 13 In *pink*, the location and extent of the anatomical supplementary motor area (SMA) defined as the interhemispheric portion of F1 that lies above the cingulate sulcus between the anterior callosal (AC) line and the precentral sulcus. The paracentral lobule of the central area is situated between the mid-calossal line (MC) and the posterior callosal line (PC). MC is a useful landmark at surgery. Note that a resection along the interhemispheric part of F1 can be taken safely back to the mid-callosal line, which is anterior to the paracentral lobule. Resection of the SMA region may result in a temporary SMA syndrome, especially in the dominant hemisphere, a possibility that must be discussed thoroughly with the patient and family prior to surgery. *HP* horizontal callosal plane. Reprinted with the permission of Cambridge University Press [1].

Supplementary Motor Area

SMA stimulation generally results in movements involving multiple muscle groups or fragments of complex actions that contrast with simple flexion or extension responses resulting from MI stimulation. Foerster and Penfield described SMA stimulation responses as either: assumption of posture, maneuvers such as stepping, or rapid incoordinate movements [12, 13] (Figs. 13 and 14). Specific motor responses also observed with SMA stimulation have included turning of the

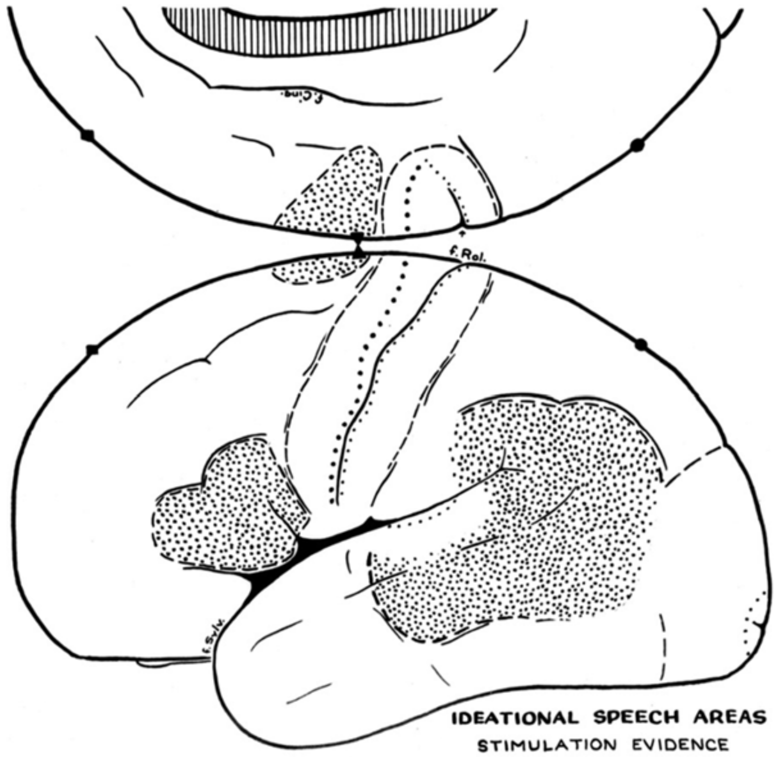

Fig. 14 The three main areas of speech function as inferred from electrical stimulation. Anterior, superior, and posterior speech zones (Corresponding to Broca's, SMA, and Wernicke's areas, respectively). Republished with permission of Princeton University Press, from Speech and Brain Mechanisms, Penfield W and Roberts L, 1959; permission conveyed through Copyright Clearance Center, Inc.

eyes and head, stepping movements, waving, and other complex hand movements. Motor responses now recognized as specific to the SMA has been described as a "fencing posture," which consists of contralateral abduction of the arm with external rotation of the shoulder and flexion at elbow.

Removal or disconnection of the SMA may result in transient postoperative deficits in motor strength and initiation of movements. In the dominant hemisphere a language disturbance of word finding difficulty is likely that can range from mild to severe (Fig. 14). A permanent deficit is not expected provided the primary motor area or its white matter fiber tract is not disrupted and the vasculature of the central area is preserved.

The possibility of a transient SMA syndrome must be discussed fully with the patient and family prior to surgery. Typically after an SMA syndrome develops, the family is more concerned than the patient with the language or motor disturbance. Since the language and motor dysfunction is transient and the patient and family are fully aware of the possibility prior to surgery, such an occurrence is considered a side effect and not a complication of surgery.

Surgical Anatomy of the Frontal Lobe (Figs. 2, 3, 4, 9, 10)

The frontal lobe is that large part of the hemisphere located anterior to the central sulcus. Laterally, the sylvian fissure separates it from the temporal lobe. Its mesial limit is the interhemispheric fissure. On the mesial surface the frontal lobe is separated from the cingulate gyrus by the cingulate (or callosomarginal) sulcus (Fig. 5). For practical purposes the anterior cingulate gyrus can be considered part of the frontal lobe although not strictly a part of the classical anatomical description of the frontal lobe.

The anatomy of the central sulcus was considered in detail above. The precentral sulcus is a deep sulcus divided by a large anastomotic root or pli de

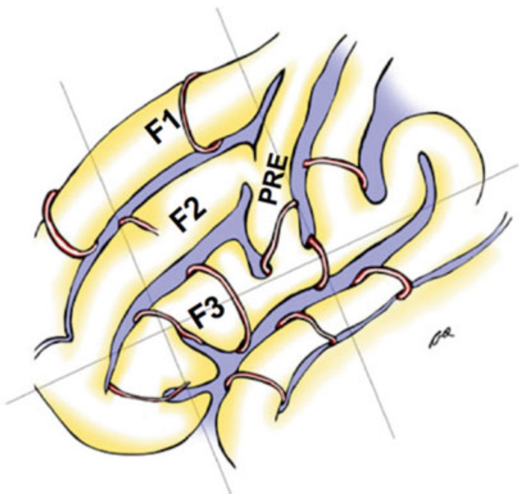

Fig. 15 Anatomy of the frontal lobe over the lateral convexity: *PRE* precentral gyrus, *F1* first frontal gyrus, *F2* second frontal gyrus, *F3* third frontal gyrus. The three plis de passage (or gyral continuum) are robust gyral connections of the precentral gyrus with F1, F2, and F3. Reprinted with the permission of Cambridge University Press [1].

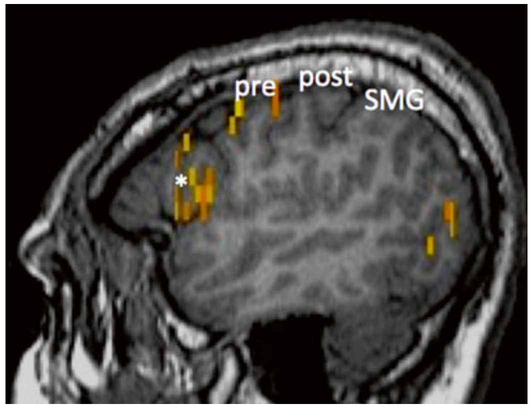

Fig. 16 FMRI activation in Broca's area (*asterisk*), which is the anatomical pars opercularis of F3 [14]. Activation in Broca's area is best seen with word seeking functional imaging tasks such as word generation and confrontation naming [15]. *pre* precentral gyrus, *post* postcentral gyrus, *SMG* supramarginal gyrus

passage that joins the precentral gyrus with the second frontal gyrus (F2) (Fig. 15). The superior frontal sulcus separates F1 from F2 on the convexity surface of the hemisphere. It is usually shallow and may be interrupted by anastomotic bridges. The inferior frontal sulcus separates F2 from F3. Opercular frontal arteries arch over F3 then disappear into the sulcus helping to outline and identify the gyrus (Fig. 15). The inferior frontal sulcus is an important landmark separating F2 from the language cortex of Broca's area of F3 in the dominant hemisphere, which then continues onto the orbital frontal surface to form the internal orbital sulcus.

Three frontal gyri take origin from the precentral gyrus as a continuous cortical and white matter pli de passage (Fig. 15). The superior frontal gyrus is best named the first frontal gyrus (F1) since it does not occupy only a superior position but extends to the orbital and mesial surfaces. It is the only gyrus found on the three surfaces of the frontal lobe, hence its subdivision into three distinct parts: external, internal, and orbital (Figs. 5, 6, 15). The posterior aspect of internal F1 behind the anterior callosal plane corresponds to the anatomical SMA (Fig. 13).

The second frontal gyrus (F2) is located on the lateral and orbital surfaces between the first and third frontal gyri (Figs. 3 and 15). F2 is the largest of the three transverse frontal gyri. It is divided into two anatomical parts, external and orbital, that occupy a large portion of the convexity and orbital surfaces. Like F1, its external portion arises from the precentral gyrus by a large plis de passage.

The third frontal gyrus (F3) between the inferior frontal sulcus and the sylvian fissure is further divided into three parts or pars, which from posterior to anterior are: pars opercularis covering the anterior insula, pars triangularis, and pars orbitalis. At surgery, the frontal opercular arteries are seen to course over F3 then dive into the inferior frontal sulcus (Fig. 15). The pars opercularis in the dominant hemisphere is the anatomic Broca's area (Figs. 3, 14, 16). The pars opercularis is connected with the precentral gyrus through a strong plis de passage gyral continuum, and the opercular pars is a continuous gyral ribbon with the pars triangularis, which flows into the pars orbitalis.

Surgical Anatomy of the Parietal Lobe

Although the central area is functionally distinct from both the frontal and parietal lobes, the postcentral gyrus is anatomically included in the parietal lobe. Posteriorly the boundary on the mesial surface is an obvious parieto-occipital sulcus.

More ill defined is the lateral convexity limit of the parietal lobe; typically the anatomical separation between parietal and occipital lobes as well as temporal and occipital lobes is a line drawn from the parieto-occipital sulcus supero-medially to the preoccipital notch inferiorly (Figs. 3, 5, 17, 18). The anterior inferior boundary of the parietal lobe corresponds to the sylvian fissure, but more posteriorly an arbitrary line must be drawn from the sylvian fissure to the occipital lobe. The inferior boundary of the parietal lobe on the mesial surface is the subparietal sulcus, a discontinuous sulcus that separates the precuneus from the cingulate gyrus (Fig. 5).

The key to defining the gyral anatomy on the convexity of the parietal lobe is the intraparietal sulcus (named interparietal sulcus by the French school). Although presenting numerous minor variations, the intraparietal parietal sulcus forms a "T" lying on its side. The vertical part is the postcentral sulcus with frequent small gyral bridges or accessory sulci crossing the sulcus, and the horizontal arm is deep and constant dividing the parietal lobe into superior and inferior lobules (Figs. 17 and 18). The horizontal limb of the intraparietal sulcus continues into the occipital lobe as the superior occipital sulcus. The superior parietal lobule (P1) includes all the area found on the convexity above the intraparietal sulcus.

P1 is continuous anteriorly with the postcentral gyrus through a plis de passage as well as continuing posteriorly to become the first occipital gyrus (Figs. 17 and 18). The convolution of the superior parietal lobule is named the precuneus on the mesial surface of the brain. The precuneus is bounded inferiorly by the subparietal sulcus, and posteriorly by the parieto-occipital sulcus (Fig. 5).

The inferior parietal lobule (P2) contains both the supramarginal and angular gyri. The supramarginal gyrus caps the posterior termination of the sylvian fissure just posterior to the lower

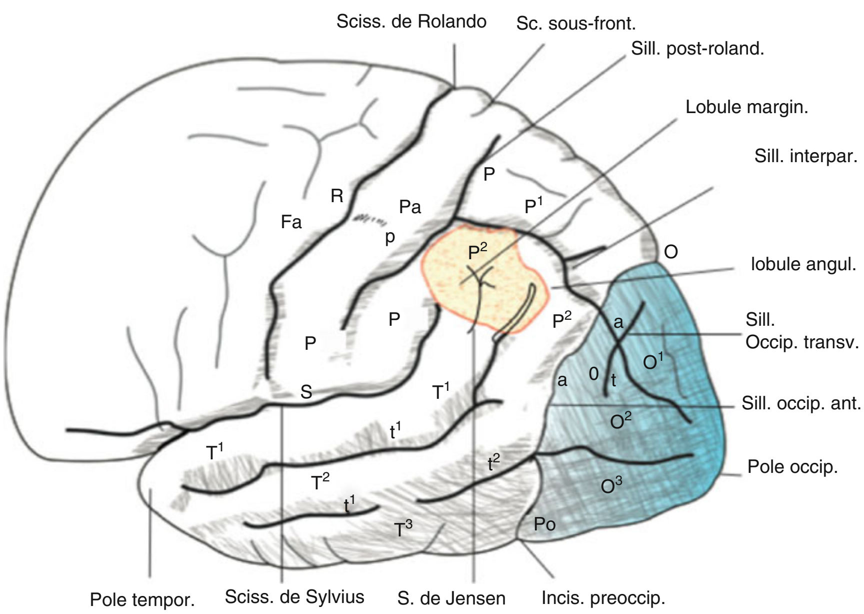

Fig. 17 The parieto-occipital area after Poirier and Charpy, 1898. The parietal lobe comprises the postcentral gyrus (Pa), the superior parietal lobule (P1), and the inferior parietal lobule (P2). The superior temporal gyrus (T1) bifurcates to form the posterior limb of the supramarginal gyrus and the anterior limb of the angular gyrus. P1 is continuous with O1, the superior occipital gyrus. The middle temporal gyrus (T2) and the angular gyrus come together to form the middle occipital gyrus (O2). The inferior temporal gyrus (T3) continues into the inferior occipital gyrus (O3). Taken together the supramarginal and angular gyri form the inferior parietal lobule (P2), which is separated from P1 by the intraparietal sulcus (sill interpar), which the French call the interparietal sulcus. P2 is eloquent in the dominant hemisphere

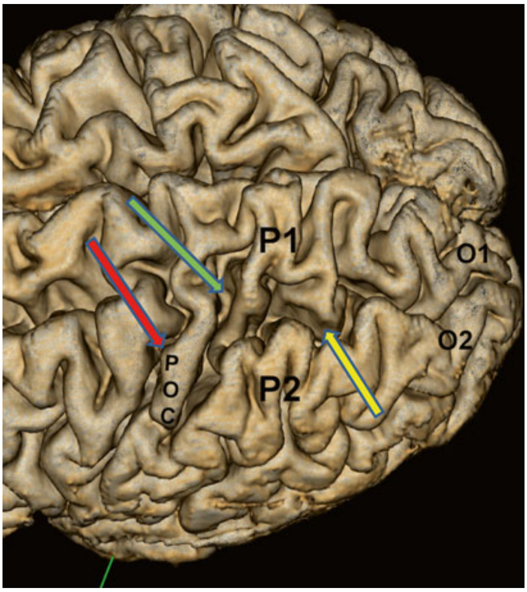

Fig. 18 Topography of the left parietal lobe. Lateral surface showing the horizontal limb of the intraparietal sulcus (*yellow arrow*) separating the superior (P1) and inferior (P2) parietal lobules. Its vertical limb corresponds to the postcentral sulcus (*green arrow*). The intraparietal sulcus is critical to identify as the sulcus separates eloquent (P2) from noneloquent (P1) cortex in the dominant parietal lobe. The sulcus continues into the occipital lobe to become the superior occipital sulcus. *POC* postcentral gyrus. Reprinted with the permission of Cambridge University Press [1].

postcentral gyrus with which it is continuous through a plis de passage. The angular gyrus is posterior to and continuous with the supramarginal gyrus and caps the posterior termination of the superior temporal sulcus (Fig. 17). There often is considerable variation in the gyral pattern of the inferior parietal lobule, such as the presence of accessory supramarginal or angular gyri interposed within the classical pattern described. However, P2 is eloquent cortex in the dominant hemisphere. Stimulation in dominate P2 frequently is able to pinpoint a cortical region that produces speech arrest. Despite appearance of a discreet language area, the posterior language area of Wernicke is not as compact as the anterior Broca's area, and resections of P2 are likely to result in some degree of language disturbance. Therefore, considerable caution must be taken in resection of potentially functioning cortex in P2 even if no speech arrest is gotten with cortical stimulation, such as in the case of epilepsy or low grade glioma. An additional challenge to surgery in P2 is that language functional imaging has proven to be less useful to pinpointing Wernicke's speech area than for Broca's area or SMA (Figs. 14, 16, 19).

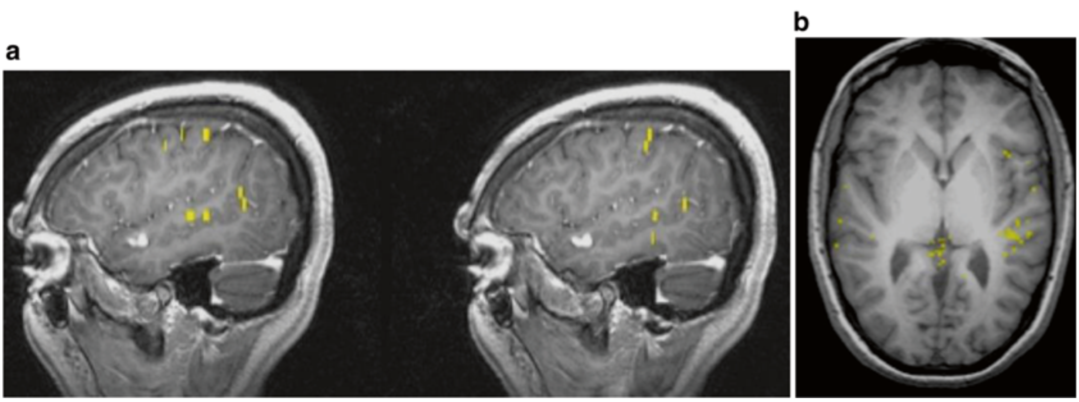

Fig. 19 Sagittal (a) and axial (b) reconstruction of language task FMRI. Wernicke's area encompasses a large cortical region that includes posterior temporal (T1 and T2) as well as inferior parietal lobule (P2). Passive tasks with functional imaging bring out posterior language activation [15]. In this case, the task was story listening. As is typical, in this FMRI study posterior temporal regions demonstrated more activation with posterior language tasks. However, P2 cannot be ruled out as eloquent and important functioning cortex

Surgical Anatomy of the Temporal Lobe (Figs. 4, 6, 7, 18)

The temporal gyri are oriented longitudinally around the temporal lobe. In a coronal oriented MRI, each gyrus is identified in cross section. They are named as the first or superior (T1), second (T2), third (T3), fourth or fusiform (T4), the fifth or parahippocampal (T5), the sixth or hippocampus proper (T6), and the seventh or dentate gyrus (T7). The first three gyri are found on the external surface of the lobe. Posteriorly, T1 merges into the supramarginal and angular gyri within the inferior parietal lobule. T2 is widest and the most prominent temporal gyrus on the external surface. Its superior and posterior extent merges into the angular gyrus within P2 and O2 of the occipital lobe, respectively. The third temporal gyrus (T3) occupies the inferolateral corner of the lobe. T3 continues along the floor of the middle fossa to become O3.

Posterior T1 and T2 in the dominant hemisphere are critical for language (Fig. 14). In dominant hemisphere temporal resections, the precentral sulcus is the anatomic landmark for the posterior extent of corticetomy along T1. More posterior surgery along T1 and T2 generally requires awake craniotomy to confirm presence of potentially normal functioning cortex and white matter prior to removal and disconnection.

Surgical Anatomy of the Occipital Lobe

The occipital lobe is the cerebral region posterior to the parieto-occipital sulcus, a medial brain surface landmark. A virtual line drawn from the most superior aspect of the parieto-occipital sulcus to the preoccipital notch anatomically demarcates the occipital lobe on the lateral convexity. The most characteristic surface feature of the occipital lobe is the calcarine fissure that contains the primary visual cortex. It is confined to the mesial surface and continuous with the parieto-occipital sulcus (Fig. 5). The calcarine fissure posteriorly separates the occipital lobe into the cuneus (O6) above and the lingual gyrus (O5) below. The calcarine fissure bulges into the occipital horn of the ventricle to form the calcar avis. O5 merges with T5 (parahippocampal gyrus) anteriorly. O4 corresponds to the occipital continuation of T4 (fusiform gyrus) (Fig. 6). The gyral pattern over the convexity of the occipital lobe can generally be divided into three separate convolutions, the superior, middle, and inferior occipital gyri (O1, O2, and O3) (Figs. 3, 17, 18), which posteriorly come together to form the occipital pole.

The primary visual cortex along with the geniculocalacarine fiber tract must both be considered when evaluating the risk of visual field deficit from surgery. The fiber tract takes origin from the lateral geniculate ganglion then runs within the sub and postlenticular segment of the internal capsule in close proximity to the temporal horn and atrium of the lateral ventricle as a distinct bundle called the external part of the stratum that is separated from the ependyma by commissural fibers that form the tapetum. Fibers from the superior retinal fields pass almost directly posterior to the superior lip of the calcarine fissure. Fibers from the inferior retinal fields loop into the temporal lobe with the most peripheral visual fibers more anterior while the macular fibers mostly bypass the temporal lobe.

Surgery of the inferior parietal and posterior temporal regions must consider the prospect of a visual field deficit resulting from disruption of the geniculocalcarine fiber tract. Of course in occipital lobe surgery, a visual field deficit including hemianopsia of the contralateral visual field is an expected side effect of surgery if no visual field deficit existed prior to surgery. In surgery for epilepsy of the occipital lobe, patients generally compensate very well if the occipital lobectomy has a reasonable opportunity to stop the seizures and the patient is thoroughly counseled on the expected hemianopsia.

Summary for the Clinician

- Sulcal and gyral patterns can reliably identify function in the sensorimotor cortex, in particular the inferior sensory cortex (tongue, lips, and thumb), whole hand area or pli de passage moyen, and foot area or paracentral lobule.
- A whole hand area exists at the pli de passage moyen in addition to individual finger somatotopic representation more inferiorly located.
- The anterior language area of Broca is confined to the posterior part of F3, pars opercularis, in the dominant hemisphere.
- All of P2 including the posterior T1 and T2 is eloquent in the dominant hemisphere.
- The SMA can be defined by anatomical landmarks. Although considered the third language or superior language area, removal of the dominant SMA is expected to result in temporary language disruption that can range from mild word finding difficulty to mutism. The deficit can last for a variable length of time, but is typically days to weeks. Since this possibility of language disruption is discussed with the patient and family prior to surgery and it is a temporary deficit, such an occurrence is a side effect of surgery and not a complication.
- Visual fiber pathway anatomy must be considered in surgery of the inferior parietal and posterior temporal regions. The possibility of a visual field deficit should be discussed with the patient prior to surgery in these areas.

Conclusion

Neuronavigation has greatly improved the ability to identify the gyral and sulcal anatomy of the brain. Even important functioning cortex such as the primary sensorimotor area and the pars opercularis of F3 containing Broca's language area can be reliably localized with neuronavigation at surgery. Cortical stimulation is required much less frequently nowadays due to availability of quality imaging and navigation capabilities. However, when surgery is performed within or very nearby important functioning cortex awake craniotomy and cortical stimulation should be performed to improve the safety of surgery and preserve critical function.

This chapter has emphasized that a thorough knowledge of the regional cortical anatomy is crucial to avoid complications of a neurological deficit from a resection. Although, it must be stated that preservation of critical function requires an equal emphasis on knowledge of the anatomy of the white matter pathways. The most important in the context of this chapter's discussion are the corticospinal tract and arcuate fasciculus in the dominant hemisphere as well as the geniculocalcarine pathway. The corticospinal tract is a robust fiber tract that can be traced with diffusion tensor imaging (DTI) and with most modern navigation platforms brought into the neuronavigation environment to navigate during surgery. The arcuate fasciculus has many crossing fibers that make DTI tract tracing more difficult. For this critical white matter pathway, cortical landmarks are most useful for identifying and avoiding disruption of language. Fiber tract stimulation is also an option during surgery, which has been used mostly for corticospinal tract localization. The geniculocalcarine pathway has a close relationship with the outer wall of the ventricle of the posterior temporal and parietal lobes. A visual field disturbance resulting from surgery should always be considered in surgery of the posterior temporal, inferior parietal, and occipital regions. A highly recommended authoritative neuroanatomy textbook is Human Central Nervous System by Nieuwenhuys et al. [16]. The book is an excellent resource for anatomical details and with precise illustrations that complement this chapter's practical discussion.

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