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PRACTICAL GUIDE

A practical guide for the identification of major sulcogyral structures of the human cortex

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Abstract The precise sulcogyral localization of cortical lesions is mandatory to improve communication between practitioners and to predict and prevent post-operative deficits. This process, which assumes a good knowledge of the cortex anatomy and a systematic analysis of images, is, nevertheless, sometimes neglected in the neurological and neurosurgical training. This didactic paper proposes a brief overview of the sulcogyral anatomy, using conventional MR-slices, and also reconstructions of the cortical surface after a more or less extended inflation process. This method simplifies the cortical anatomy by removing part of the cortical complexity induced by the folding process, and makes it more understandable. We then reviewed several methods for localizing cortical structures, and proposed a three-step identification: after localizing the lateral, medial or ventro-basal aspect of the hemisphere (step 1), the main interlobar sulci were located to limit the lobes (step 2). Finally, intralobar sulci and gyri were identified (step 3) thanks to the same set of rules. This paper does not propose any new identification method but should be regarded as a set of practical guidelines, useful in daily clinical practice, for detecting the main sulci and gyri of the human cortex.

Keywords Cerebral cortex · Anatomy · MRI · Localization

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Introduction

Precise anatomical localization of cortico-subcortical lesions or functional activations is important for several reasons. First, it is a major tool for communication between people taking care of a patient and provides a gross evaluation of post-operative functional risks. Second, functional imaging informs on function and connectivity of eloquent brain areas, but results of functional magnetic resonance imaging (MRI) or diffusion-weighted imaging tractography only make sense when interpreted in the light of the underlying anatomy. This localization can use cytoarchitectonics, coordinates, or the sulcogyral pattern, the latter being the only non-invasive option available in daily clinical practice.

Several attempts have been made to achieve this task, leading to more or less complicated and extensive nomenclature systems for identification of cortical structures (Gratiolet 1854; Ecker 1873; Broca 1878; Cunningham 1892; Ono et al. 1990; Federative Committee on Anatomical Terminology 1998; Duvernoy 1999). Several automated atlas-based systems were developed to automatically label the human cortex (Roland et al. 1994; Lancaster et al. 2000; Rettmann et al. 2002, 2005; Fischl et al. 2004; Klein et al. 2005; Regis et al. 2005; Clouchoux et al. 2006; Desikan et al. 2006; Heckemann et al. 2006; Shattuck et al. 2008; Destrieux et al. 2010). Nevertheless, since these methods are generally computing-time demanding and may be confused by lesions displacing sulcogyral structures (such as tumors and edema) or modifying the MRI signal of gray and white matter (such as strokes or tumors), they are mainly used for research purposes. Thus, clinicians have to manually identify important sulci and gyri located in the vicinity of a lesion. To provide accurate labeling, this identification has to

follow a precise systematic and simple set of rules (Naidich et al. 1995; Naidich and Brightbill 1996a, b; Naidich et al. 1997; Braun et al. 2000) based on the knowledge of basic cortical anatomy.

This task is complicated by the highly convoluted surface of the human brain, which hides more or less 60 % of the cortical surface in the sulcal depth (Zilles et al. 1997; Van Essen 2005). Software has been developed to unfold the cortical surface and provide simpler views of its anatomy (Dale and Sereno 1993; Van Essen and Drury 1997; Dale et al. 1999; Fischl et al. 1999).

In this paper, we aim to provide the reader with (1) a simple description of the sulcogyral pattern using inflated representations of the brain. This description will have to be kept in mind to understand and apply (2) a set of selected rules helping the manual identification of major cortical structures on conventional anatomical MRIs. This paper is clearly not a proposal for a new nomenclature, since it mainly refers to the already standard nomenclature used in the radiological and neurosurgical fields (Ecker 1873; Duvernoy 1999). It is neither a review of possible anatomical variations that were nicely depicted elsewhere (Ono et al. 1990; Naidich et al. 1995). Instead, it should be regarded as a set of practical guidelines, useful in daily clinical practice, for detecting the main sulci and gyri of the human cortex.

Materials and methods

Data acquisition

Brain MRI from one 29-year-old normal male subject was used to illustrate this paper for both conventional and inflated representations. One high-resolution whole-head 3D T1-IR-weighted scan was collected on a 3T Verio Siemens scanner using a 32-channel coil (voxel size 0.75 × 0.75 × 0.75 mm, TR: 2200 ms, TE: 3.2 ms, TI: 900 ms, flip angle: 10°).

Conventional MR visualization

Images were transferred to OsiriX Lite 7.0.2 software (http://www.osirix-viewer.com/) running on an iMac Apple computer (Cupertino, CA, USA). Illustrative multiplanar reconstructions of major sulci were obtained in the desired plans.

Inflated reconstruction, labeling and visualization

Inflated representations of the cortical surface were used to illustrate the rules proposed in this paper. They provide a simpler representation of the cortex anatomy after getting rid of its convoluted aspect. The detailed reconstruction process of the cortical surface has previously been described in detail (Dale et al. 1999; Fischl et al. 1999) and is briefly described here. After correction for intensity variations due to magnetic field inhomogeneities, non-brain tissues were removed from the T1-weighted normalized images using a hybrid watershed/surface deformation procedure (Ségonne et al. 2004). The brain was then segmented using the signal intensity and geometric structure of the gray–white interface. Each hemisphere was automatically disconnected from the other and from the mesencephalon, resulting in two binarized white matter volumes—one for each hemisphere. The surface of each white matter volume was then tessellated with a triangular mesh, and deformed to obtain a smooth and accurate representation of the gray–white interface. After the topology of this surface was automatically corrected (Segonne et al. 2007), it was inflated in a way that retains much of the shape and metric properties of the original gray–white interface. This process unfolded the cortical sulci, leading to a representation where the whole cortical surface (i.e., sulcal and gyral) was visible. At the end of the reconstruction process, several images were available for each hemisphere: pial (no inflation, gray–CSF interface), white (no inflation, gray–white interface), inflated (inflation, gray–white interface) or semi-inflated.

The sulcogyral pattern of each hemisphere was then probabilistically segmented into 74 anatomical classes thanks to an automated procedure we previously created (Destrieux et al. 2010).

Proposed set of rules

Anatomical localization of a cortical lesion should begin by the identification of the aspect of the brain (medial, lateral, ventro-basal), then to the lobe and finally to the sulcus or gyrus it belongs to (Fig. 1). The first step—identification of the aspect of the hemisphere—is straightforward, and hence, we will only focus on steps 2 and 3 for the medial, lateral and ventro-basal aspects of the hemisphere successively. The rules are intended to be used in a clinical practice (i.e., on conventional slices), but we will also refer to surface reconstruction to better explore the cortical anatomy.

Medial aspect of the brain

Medial aspect: identification of interlobar sulci

At the medial aspect of the hemisphere, three interlobar sulci are easily recognized on both inflated reconstructions

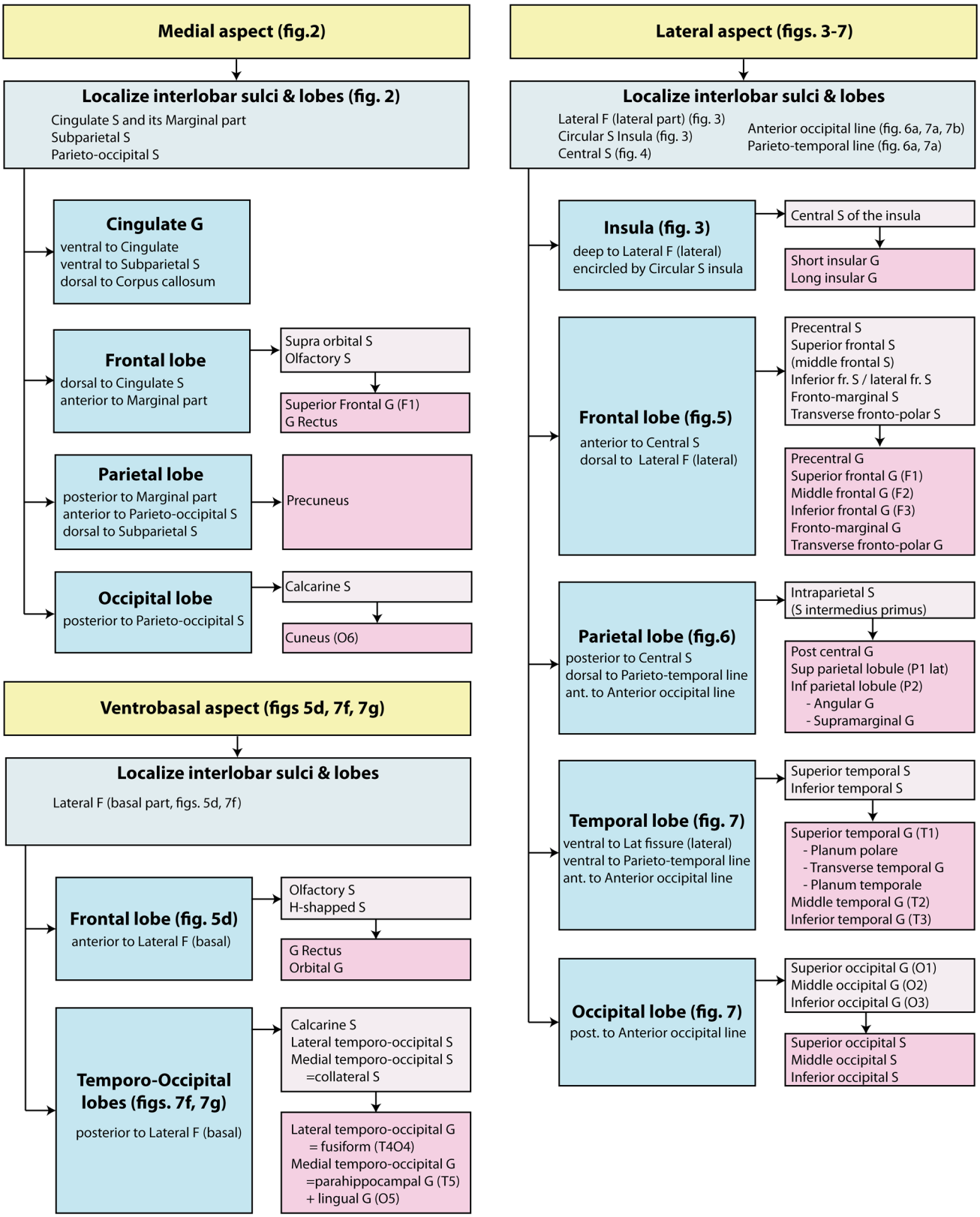


Fig. 1 Flowchart of sulcogyral identification. The localization of a cortical area has to follow a systematic three-step roadmap. Step 1: the aspect of the brain (medial, lateral or ventro-basal) is defined (*yellow boxes*). Step 2: interlobar sulci are recognized (*lighter blue boxes*) to limit the different lobes involved in the area (*darker blue boxes*). Step 3: in each lobe, identification of the intralobar sulci (*lighter pink boxes*) permits to limit the gyri (*darker pink boxes*)

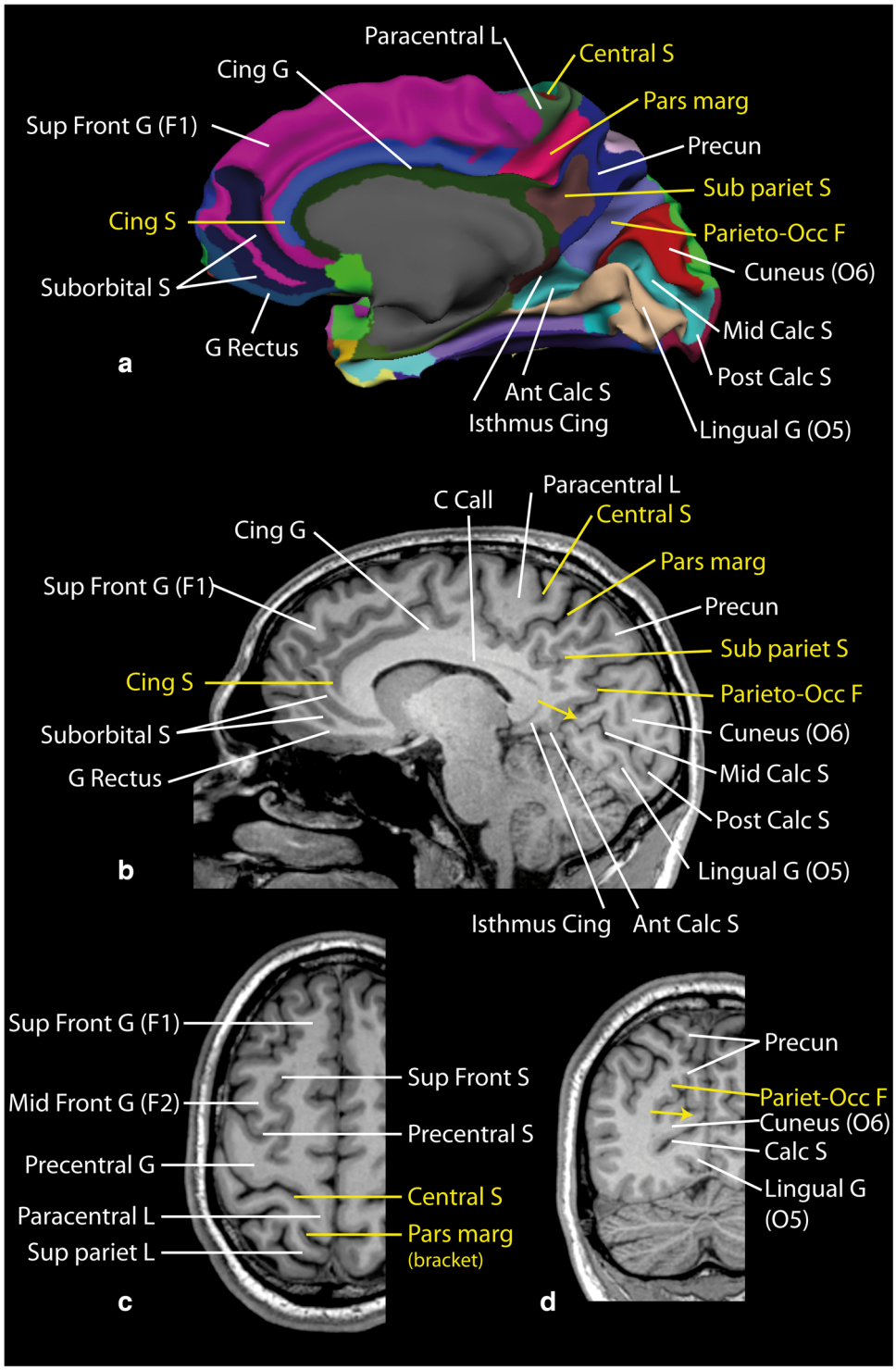


Fig. 2 Identification of the interlobar sulci of the medial aspect of the brain. Interlobar sulci (*yellow indices*), which separate different lobes can easily be recognized at the medial aspect of the brain (**a** semi-inflated view, **b** sagittal slice, **c** axial slice, **d** coronal slice): the cingulate sulcus (*Cing S*) anteriorly follows the curve of the corpus callosum and its marginal part (*Pars marg*) reaches the superior edge of the hemisphere. It limits the cingulate gyrus (*Cing G*) from the medial aspect of the superior frontal gyrus (*Sup Front G*, *F1*). On an axial plane (**c**), the pars marginalis of the cingulate sulcus appears as an anteriorly curved sulcus originating from the median sagittal fissure (*bracket sign*); the subparietal sulcus (*Sub Pariet S*) posteriorly continues the general direction of the cingulate sulcus. It limits the cingulate gyrus (*Cing G*) from the medial aspect of the parietal lobe, or precuneus (*Precun*); the parieto-occipital fissure (*Parieto-Occ F*) runs anteriorly and ventrally to reach the zigzagged calcarine sulcus (*Calc S*), the fusion of these two sulci forming the anterior part of the calcarine sulcus (*Ant Calc S*). The latter posteriorly limits the isthmus of the cingulate gyrus (*Isthmus Cing*) from the lingual gyrus or O5 (*Lingual G*). Due to this fusion, the calcarine sulcus and parieto-occipital fissure form a sharp angle having its apex (*yellow arrow*) oriented anteriorly on a sagittal plane (**b**) and medially on a coronal plane (**d**)

and slices (Figs. 1, 2): cingulate, subparietal and parieto-occipital.

The cingulate sulcus originates in the subcallosal area and has a curved course, which successively parallels the rostrum, genu and body of the corpus callosum. Close to the junction between the isthmus of the cingulum and the splenium of the corpus callosum, the marginal part of the cingulate sulcus ascends to reach the superior edge of the hemisphere. This curved course of the cingulate sulcus including its marginal part can easily be recognized on a parasagittal slice located a few millimeters lateral to the falx cerebri (Fig. 2a, b). On an axial slice located close to the vertex, this marginal part of the cingulate sulcus can also be localized as a small, anteriorly concave sulcus

originating from the interhemispheric fissure (Fig. 2c). Since marginal parts of both hemispheres usually face each other, they are sometimes described as a bracket (Naidich and Brightbill 1996b).

The subparietal sulcus, which continues the main direction of the cingulate sulcus around the superior aspect of the splenium of the corpus callosum, can be best seen on the parasagittal slice used for identification of the cingulate sulcus (Fig. 2a, b). It usually has an upside down "Y" shape on parasagittal slices.

The parieto-occipital fissure is a deep sulcus that originates posteriorly at the superior edge of the hemisphere, runs anterior and ventral, and joins the junction between the middle and anterior parts of the calcarine sulcus (Fig. 2a, b, yellow arrow); the calcarine sulcus is not an interlobar sulcus since it is located at the middle of the occipital lobe, between the cuneus (or O6, dorsal) and lingual gyrus (or O5, ventral). It is described here due to its major relationships with the parieto-occipital fissure (Fig. 2a, b); the calcarine sulcus is, indeed, made of three parts: (1) middle, that has a more or less horizontal and "zigzagged" course at the medial aspect of the occipital lobe; (2) posterior, that bifurcates close to the posterior tip of the occipital pole and sometimes exits the interhemispheric fissure to reach the most posterior aspect of the occipital lobe; and (3) anterior, which ends posterior and ventral to the cingulate isthmus. The parieto-occipital fissure and calcarine sulcus are best seen on the same parasagittal slice as the one depicting the cingulate and subparietal sulci (Fig. 2b). On coronal views located posterior to their union (i.e., through the middle part of the calcarine sulcus), the parieto-occipital fissure and calcarine sulcus appear as two deep sulci that medially reach the interhemispheric fissure (Fig. 2d). Due to their relative obliquity, the distance between them decreases as the coronal slice becomes more anterior. Anterior to their union, the anterior part of the calcarine sulcus appears as a deep sulcus directed toward the medial aspect of the occipital horn of the lateral ventricle where it creates a small bump, or calcar avis.

Medial aspect: identification of sulci and gyri

The organization of the main sulci at the medial aspect of the brain is simple since these interlobar sulci limit together (Figs. 1, 2):

1. the cingulate gyrus, located between the corpus callosum and cingulate sulcus/subparietal sulcus/anterior part of the calcarine sulcus (Fig. 2a, b, d);
2. the frontal lobe: the medial aspect of the superior frontal gyrus (or F1) is located above the cingulate gyrus and anterior to its marginal part. It sometimes contains an additional discontinuous supracingulate sulcus, more or less connected to the cingulate sulcus. At the junction between the medial and ventral aspects of the frontal lobe, the gyrus rectus is dorsally limited from the superior frontal gyrus by the suborbital sulcus, which parallels the ventral part of the cingulate sulcus. A second suborbital sulcus sometimes runs parallel and dorsal to it (Fig. 2a, b);
3. the parietal lobe (precuneus, or medial P1) which is located dorsal to the subparietal sulcus, posterior to the marginal part of the cingulate sulcus, and antero-dorsal to the parieto-occipital fissure (Fig. 2a, b, d);
4. the cuneus, (O6), one of the two occipital gyri visible at the medial aspect of the brain with the lingual gyrus. It forms a triangle located between the parieto-occipital fissure anteriorly, and the calcarine sulcus ventrally (Fig. 2a, b, d). The lingual gyrus will be described within the ventro-basal aspect of the brain section.

Lateral aspect of the brain

Lateral aspect: identification of interlobar sulci

Three interlobar sulci divide the lateral aspect of the hemisphere (Fig. 1): the lateral part of the lateral fissure, the circular sulcus of the insula and the central sulcus. The lateral part of the lateral fissure is easily recognized on sagittal slices lateral to the insula, where the frontal and parietal lobes face the temporal lobe (Fig. 3). It is divided in three segments: (1) middle, gently ascending posteriorly and parallel to the main axis of the temporal lobe, (2) posterior, ascending into the parietal lobe, and (3) anterior, that rapidly divides into vertical and horizontal rami (Fig. 3a). On coronal views, the lateral fissure opens into the lateral fossa, medially limited by the insula. Put together, on coronal slices, the lateral fossa and fissure resemble a "T" letter lying on its side (Fig. 3c).

The insula (Fig. 3b, c) is located deep in the lateral fossa and limited from the surrounding frontal, parietal and temporal opercula by the circular sulcus of the insula. This sulcus is best seen on a sagittal plane reoriented on coronal and axial view to follow the main plane of the insula (Fig. 3b). It appears as a triangle made of three segments: inferior (border with the temporal operculum), superior (limit with the frontal and parietal operculum), and anterior (limit to the orbital gyri). The superior and inferior parts posteriorly fuse to form the posterior segment of the lateral fissure, while the anterior and inferior parts join close to the limen insulae.

The central sulcus is more complicated to localize and a good knowledge of the anatomy of the surrounding

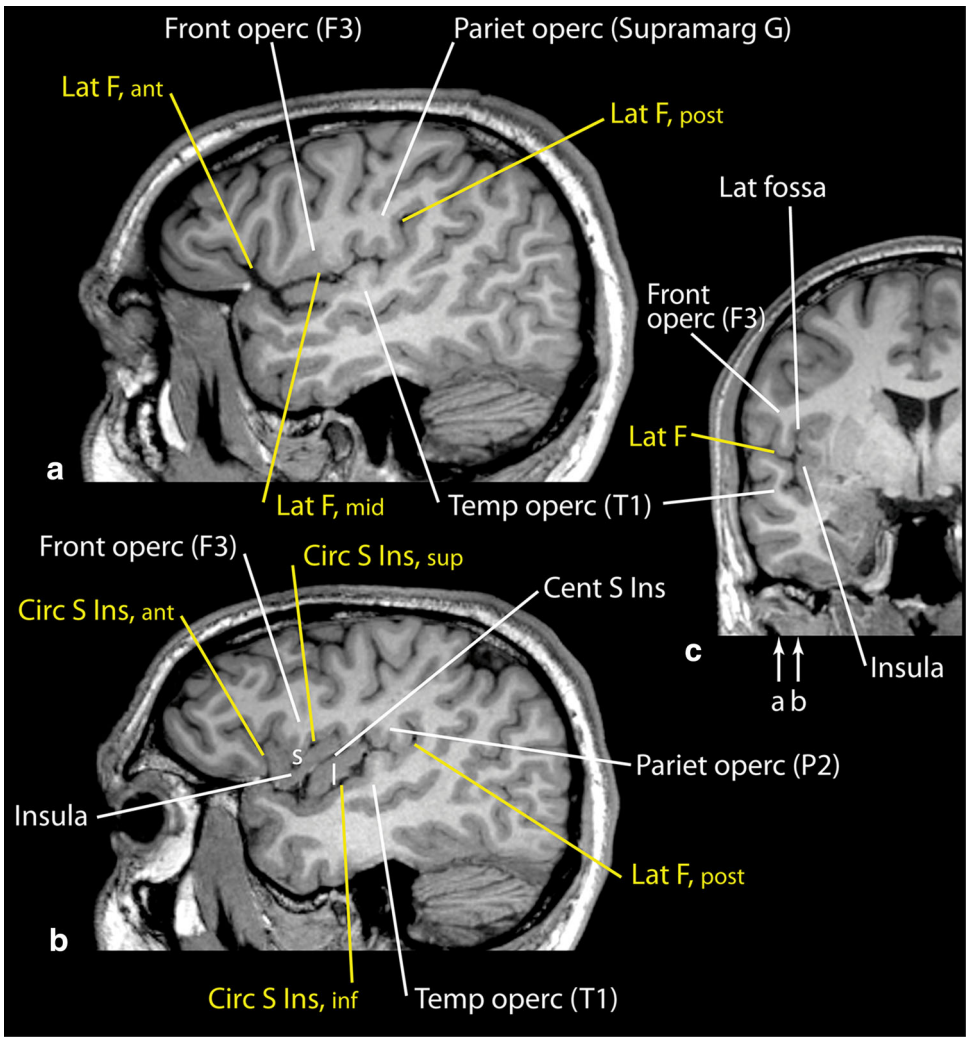


Fig. 3 Identification of the lateral fissure and circular sulcus of the insula. The lateral fissure is made of a basal part, visible at the ventral aspect of the brain, and a lateral part visible at its lateral aspect. **a** (Sagittal slice): the lateral part of the lateral fissure can be easily identified on a lateral sagittal plane. Its *anterior segment* (Lat F, ant) divides into vertical and horizontal rami. It is continued by the *middle segment* (Lat F, mid), which gently ascends posteriorly to become the *posterior*, more abruptly ascending, *segment* (*Lat F*, *post*). The lateral part of the lateral fissure limits the fronto-parietal operculum (*Front operc* and *Pariet operc*) from the temporal one (*Temp operc*). **b** (Sagittal slice): the circular sulcus of the insula (*Circ S Ins*) can be studied on a sagittal plane located a few millimeters more medial than **a**. It is made of anterior, superior and inferior segments limiting the insula from the surrounding opercula. Posteriorly, the posterior segment of the lateral fissure continues the superior and inferior segments of the circular sulcus of the insula. The short (s) and long (l) gyri of the insula are limited by the central sulcus of the insula (*Cent S Ins*) joining the superior and inferior parts of the Circular sulcus of the insula. **c** (Coronal slice): the lateral part of the lateral fissure enlarges medially to form the lateral fossa (*Lat fossa*) which faces the insula. *Arrows* **a**, **b** show the level of the corresponding sagittal planes. *Yellow indices* show interlobar sulci, whereas *white ones* show intralobar sulci/gyri

sulci –nicely depicted on the semi-inflated views (Fig. 4b, d, f)—is mandatory for its identification (Fig. 4); the central sulcus originates at the superior edge of the hemisphere, just anterior to the marginal part of the cingulate sulcus, runs ventrally and anteriorly towards the lateral fissure that it does not reach (Fig. 4a, b). The precentral sulcus parallels the central sulcus and is usually divided into a superior and an inferior segment. These segments, respectively, connect orthogonally with the superior and inferior frontal sulci that run more or less horizontally in the frontal lobe. Posterior to the central sulcus, the postcentral sulcus also parallels the central sulcus and its inferior tip ends between the central sulcus and posterior tip of the lateral fissure. It is posteriorly continued by the intraparietal sulcus. Several rules may be used to localize the inferior, middle and superior segments of the central sulcus:

- To localize the inferior tip of the central sulcus (Fig. 4a, b), the sagittal slice showing the vertical and horizontal

rami of the anterior segment of the lateral fissure has to be selected (Fig. 4a). The horizontal sulcus located just above these two rami is the inferior frontal sulcus, which posteriorly connects at right angle to the inferior segment of the precentral sulcus. The central sulcus is located just posterior to the latter.

The identification of the inferior tip of the central sulcus may be confirmed on the same sagittal slice (Fig. 4a) showing the posterior tip of the lateral fissure surrounded by the supramarginal gyrus (see below, parietal lobe). Three parallel sulci are located anterior to the posterior tip of the lateral fissure, from posterior to anterior: postcentral, central and precentral.

- The middle part of the central sulcus may be localized thanks to the junction between the superior frontal sulcus and the precentral sulcus (Fig. 4c). On axial views inspected in a descending direction from the vertex, the superior frontal sulcus is easily localized as the first antero-posterior continuous sulcus running parallel to the midline (Fig. 4c). The slice best depicting the superior frontal sulcus is usually located 2–3 cm from the vertex, which helps in differentiating it from the more lateral and ventral inferior frontal sulcus. Once the superior frontal sulcus is localized, the superior segment of the precentral sulcus can be identified as a descending sulcus branching perpendicular to it, and the central sulcus is located just posterior to it.

  Just posterior and ventral to the superior-frontal/precentral sulcus junction, the precentral gyrus has an anteriorly concave curved course that usually corresponds to the primary motor cortex of the hand (Fig. 4d). This "omega sign" is best seen on axial slices located a few millimeters ventral to the junction between the precentral and superior frontal sulci. Nevertheless, it has to be used with caution since the postcentral gyrus sometimes follows the same curved course. Finally, the middle part of the precentral gyrus may be localized thanks to additional signs: its thickness (Fig. 4d) exceeds that of the postcentral gyrus (Meyer et al. 1996; Fischl and Dale 2000), and it has a lower signal intensity on turbo FLAIR images (Karaarslan and Arslan 2003).

- The superior tip of the central sulcus is best localized on a parasagittal view depicting the cingulate sulcus: the superior tip of the central sulcus centers the parasagittal lobule meaning that it is the first sulcus anterior to the marginal part of the cingulate sulcus (Fig. 4e). Similarly, on axial view (Fig. 4g), the central sulcus superiorly ends just anterior to the "brackets" corresponding to the marginal part of the cingulate sulci (see medial aspect).

Once located, the lateral fissure, circular sulcus of the insula and central sulcus limit (Fig. 1):

1. The insula, encircled by the circular sulcus of the insula.
2. The frontal lobe, located anterior to the central sulcus and dorsal to the lateral fissure.
3. The parietal lobe, located just posterior to the central sulcus and dorsal to the lateral fissure.
4. The temporal lobe, located ventral to the lateral fissure.

The anterior limit of the occipital lobe is unclear at the lateral aspect of the hemisphere, only marked by an inconstant temporo-occipital notch, sometimes continued by an ascending anterior occipital sulcus. A virtual curved line joining the inferior to the superior edges of the hemisphere was, therefore, proposed (Figs. 6, 7): It runs between the temporo-occipital notch and the superior tip of the parieto-occipital fissure. Nevertheless, precise localization of lesions of this temporo–parieto–occipital "crossroad" is quite difficult.

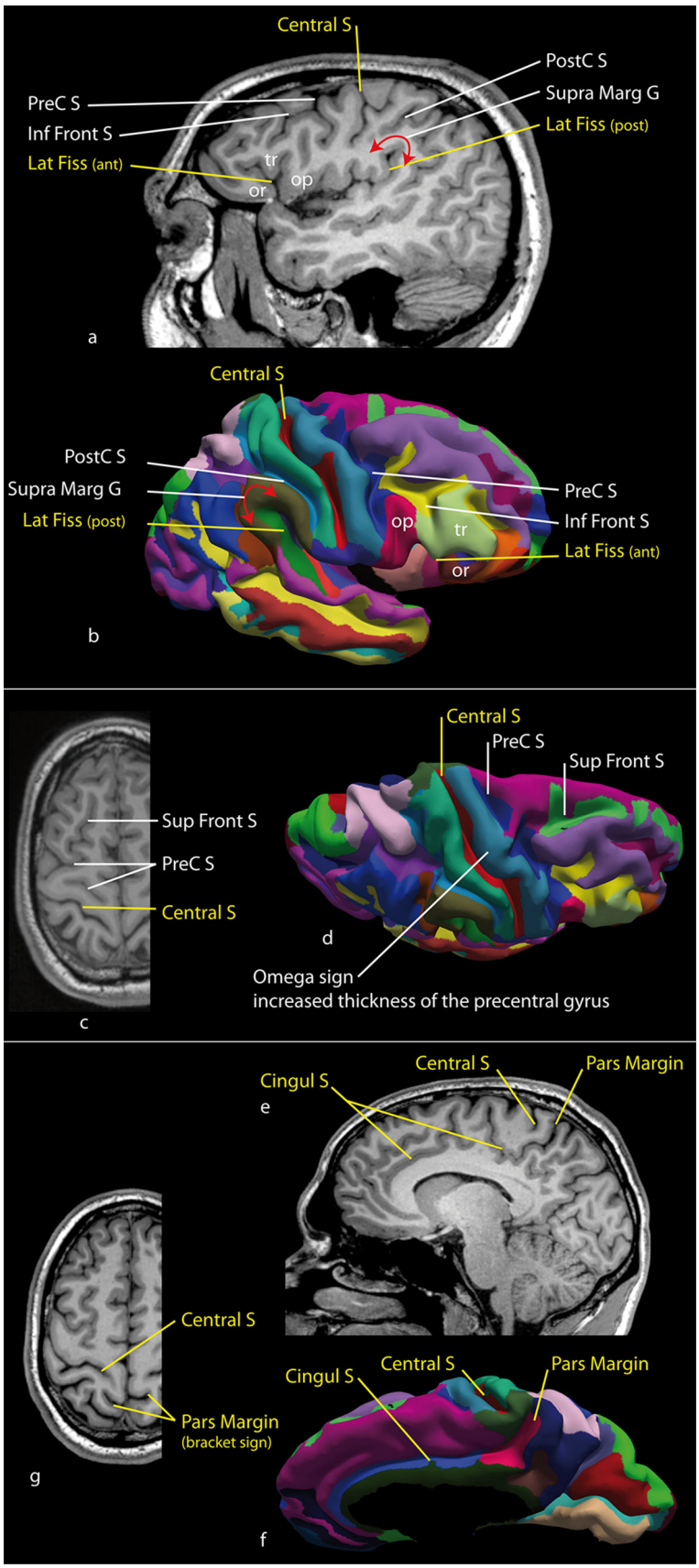
Lateral aspect: identification of intralobar sulci and gyri

In this section, identification rules for the insula, frontal, parietal, temporal and occipital lobes will be successively provided.

Sulci and gyri of the insula can only be properly studied on appropriate oblique sagittal view that has to be parallel to the plane of the insula in both axial and coronal views (Fig. 3). The insula is divided by the central sulcus of the insula, which joins the superior and inferior segments of the circular sulcus of the insula and continues the direction of the central sulcus. The central sulcus of the insula divides the insular cortex into long insular gyri posteriorly (usually two gyri) and short insular gyri anteriorly (usually three gyri).

The main sulci and gyri dividing the lateral aspect of the frontal lobe (Fig. 5a–c) were previously described: the precentral gyrus is a strip of cortex located between the central and precentral sulci from which it follows the orientation. It is limited from the horizontally directed superior frontal gyrus by the upper part of the precentral sulcus. The superior frontal gyrus (or F1) extends from the superior frontal sulcus on the lateral aspect of the brain, to the cingulate sulcus on its medial aspect. It sometimes contains an additional interrupted sulcus on its lateral aspect, the medial frontal sulcus. The later, which courses antero-posteriorly, parallels the superior frontal sulcus but is discontinuous.

The inferior frontal gyrus (or F3, Fig. 5a, b) is located between the superior segment of the circular sulcus of the


Central S
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Central S
PreC S
Sup Front S
d
Omega sign
increased thickness of the precentral gyrus
Cingul S
Central S
Pars Margin
e
Central S
Pars Margin
(bracket sign)
g
Cingul S
Central S
Pars Margin
f

◀**Fig. 4** Identification of the central sulcus. *Superior panel* (**a**, **b**): the inferior part of the central sulcus (*Central S*) can be identified by two sets of rules on a sagittal slice passing through the anterior part of the lateral fissure (**a**) or on a lateral right semi-inflated representation of the cortical surface (**b**): from *anterior* to *posterior* (**a**, **b**) after identifying the anterior segment of the lateral fissure (*Lat Fiss ant*, see Fig. 3), search for the inferior frontal sulcus (*Inf Front S*), a horizontal sulcus running just dorsal to it. The latter branches at right angles with the inferior part of the precentral sulcus (*PreC S*), located just anterior to the central sulcus. The inferior frontal sulcus dorsally limits the inferior frontal gyrus, made of parts orbital (or), triangular (tr) and opercular (op); from *posterior* to *anterior* (**a**, **b**) first identify the posterior tip of the lateral fissure (*Lat Fiss post*), surrounded by the supramarginal gyrus (*Supra Marg G*). The anterior limit of the supramarginal gyrus is the postcentral sulcus (*PostC S*), which posteriorly parallels the central sulcus. *Middle panel* (**c**, **d**) identification of the middle segment of the central sulcus on an axial slice (**c**) and semi-inflated supero-lateral view of the right hemisphere (**d**). The superior frontal sulcus (*Sup Front S*) is easily recognized as a longitudinal, continuous sulcus, which parallels the superior edge of the hemisphere. It posteriorly joins the precentral sulcus (*PreC S*) at a right angle. The central sulcus is located just posterior. *NB:* The Omega sign and increased thickness of the cortex are other signs helping the identification of the middle segment of the central sulcus. *Inferior panel* (**e**–**g**) identification of the superior aspect of the central sulcus. On a parasagittal slice (**e**) or a semi-inflated reconstruction of the surface of the right hemisphere (**f**, *supero-medial view*), the marginal part (Pars Margin) of the cingulate sulcus (*Cingul S*) is first identified as the ascending posterior part of the cingulate sulcus; on an axial slice (**g**), both marginal parts of the cingulate sulci form an anteriorly concave curve. The superior tip of the central sulcus lies just anterior to this *bracket sign*. *Yellow indices* show interlobar sulci, whereas *white ones* show intralobar sulci/gyri

insula and inferior frontal sulcus, and is limited from the precentral gyrus by the inferior part of the precentral sulcus. After a horizontal course, the inferior frontal sulcus anteriorly takes a descending and then more or less posterior direction. This recurrent course is known as the lateral orbital sulcus, which may also be independent from the inferior frontal sulcus. The inferior frontal gyrus, that constitutes the frontal operculum, is subdivided into three parts by the horizontal and vertical rami of the anterior segment of the lateral fissure: (1) the triangular part is located between these two rami; (2) the orbital part is located between the horizontal ramus and the lateral orbital sulcus; and (3) the opercular part is limited by the vertical ramus anteriorly, and a small ascending and posteriorly concave sulcus connected to the lateral fissure, the anterior subcentral sulcus (Fig. 5a, b). The middle frontal gyrus (F2) is located between the superior and inferior frontal sulci (Fig. 5a, c). Due to the segmentation of the precentral sulcus in superior and inferior segments, and contrary to superior and inferior frontal gyri, it appears continuous with the precentral gyrus. The middle frontal gyrus is the largest frontal gyrus visible at the lateral aspect of the frontal lobe, and it is frequently subdivided by a horizontal discontinuous sulcus, the middle frontal sulcus. This sulcus, which does not connect to the precentral sulcus, reaches the frontal pole, but may be connected to the superior or inferior frontal sulci at its anterior course.

At the frontal pole (Fig. 5a, d), the longitudinal superior and middle frontal gyri are interrupted by one or several transverse gyri that are perpendicular to the midline: the fronto-marginal gyrus forms the junction of the lateral and orbital aspects of the frontal lobe at the frontal pole. It is accompanied by one or two transverse frontopolar gyri that run at its dorsal aspect and reach the midline.

The lateral aspect of the parietal lobe (Fig. 6) is divided by a large sulcal complex, sometimes described as a whole (Duvernoy 1999): the postcentral sulcus is, indeed, sometimes continuous with the intraparietal sulcus, without any sharp angle at their junction, these two sulci usually forming an inferiorly concave curve (Fig. 6a–c). Identification of the postcentral sulcus, immediately anterior to the posterior tip of the lateral fissure, was previously presented. The intraparietal sulcus parallels the midline and is posteriorly continued by the superior occipital sulcus without any clear limit (Fig. 6a, b). It is best seen on coronal sections as a deep vertical sulcus having several transverse rami (Fig. 6d). The postcentral–intraparietal sulcal complex divides the lateral aspect of the parietal lobe into: postcentral gyrus, superior and inferior parietal lobules (Fig. 6a–c). The postcentral gyrus is limited by the central and postcentral sulci and is connected to the precentral gyrus by two plis de passage: the subcentral gyrus (Fig. 6a, b) and paracentral lobule (Fig. 2a–c), respectively, located around the infero-lateral and supero-medial tips of the central sulcus. The superior (P1) and inferior (P2) parietal lobules are located posterior to the postcentral sulcus and separated by the intraparietal sulcus. The inferior parietal lobule is further subdivided into supramarginal and angular gyri, respectively, running around the posterior tips of the lateral fissure and the superior temporal sulcus. A descending inconstant sulcus branching from the intraparietal sulcus, the sulcus intermedius primus, sometimes clearly limits them (Fig. 6a, b).

As previously stated, no clear limit exists between the lateral aspects of the temporal and occipital lobes (Fig. 7). They are subdivided by two temporal (superior and inferior) and three occipital (superior, middle and inferior) sulci.

The superior temporal sulcus is deep and parallels the lateral fissure to ascend posteriorly where it sometimes divides into two branches surrounded by the angular gyrus (posterior part of the inferior parietal lobule). Conversely, the inferior temporal sulcus is less deep but discontinuous. They both reach the temporal pole (Fig. 7a, c, d). The superior and inferior occipital sulci, respectively, continue the intraparietal and inferior temporal sulci, posterior to the virtual line anteriorly limiting the occipital lobe (between

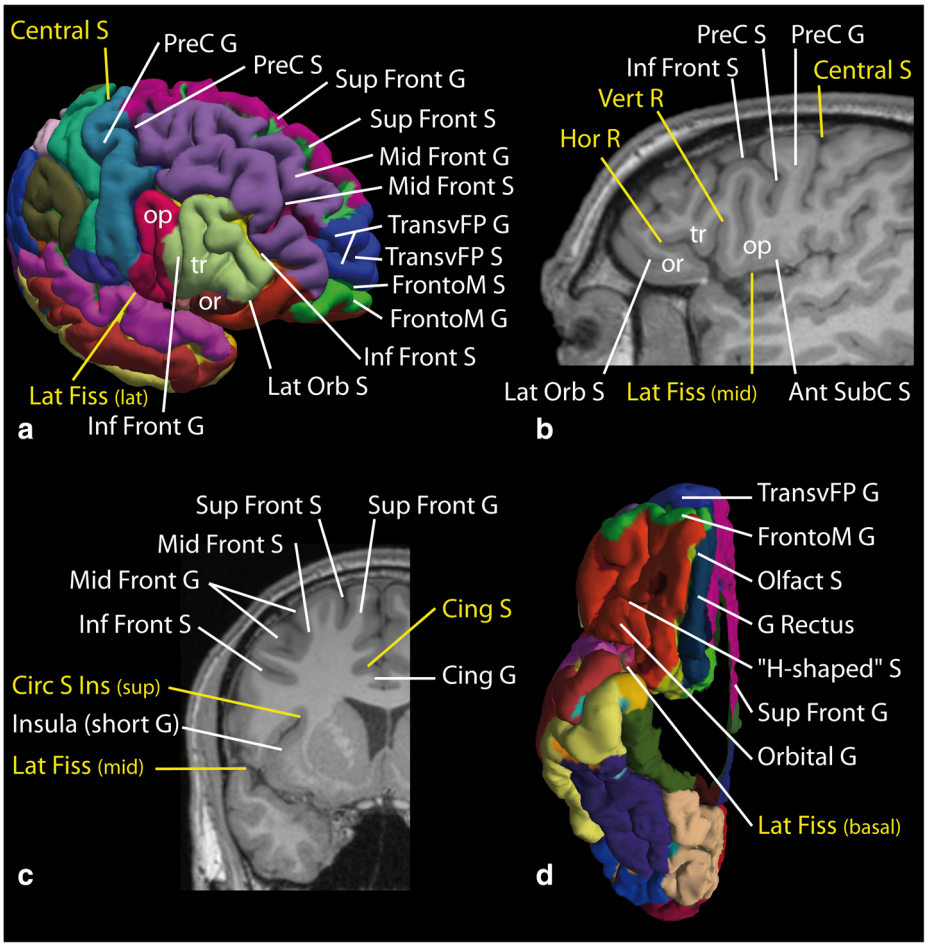


Fig. 5 Identification of the sulci and gyri of the frontal lobe (lateral and ventral aspect). The frontal lobe is limited by interlobar sulci (legended in *yellow*) that were identified in the previous steps: the central sulcus (*Central S*) postero-laterally, the lateral part of the lateral fissure (*Lat Fiss*) ventro-laterally, the cingulate sulcus (*Cing S*) medio-ventrally and its pars marginalis (*Pars Marg*) medio-posteriorly. *Laterally* (**a** cortical surface of a right hemisphere, antero-lateral view, **b** sagittal slice, **c** coronal slice), the frontal lobe is subdivided into four major gyri: the precentral gyrus (*PreC G*), located between the central and precentral (*PreC S*) sulci, which are descending from the superior edge of the hemisphere with an oblique anterior course; the superior (*Sup Front G*) and inferior frontal (*Inf Front G*) gyri, limited from the middle frontal gyrus (*Mid Front G*) by the superior (*Sup Front S*) and inferior (*Inf Front S*) frontal sulci. The inferior frontal gyrus is subdivided into partes opercularis (*op*), triangularis (*tr*), and orbitalis (*or*) by the horizontal (*Hor R*) and vertical (*Vert R*) rami of the anterior part of the lateral fissure. The pars opercularis is posteriorly limited by a small sulcus ascending from the lateral fissure, the anterior subcentral sulcus (*Ant SubC S*). The middle frontal gyrus often contains a middle frontal sulcus (*Mid Front S*) that does not reach the precentral sulcus; in the area of the frontal pole, the longitudinally oriented superior, middle, and inferior frontal gyri are interrupted by several transverse gyri and sulci: the frontomarginal gyrus (*FrontoM G*) is a strip of cortex located at the junction between the lateral and ventral (or orbital) aspects of the frontal pole. It is limited from the transverse frontopolar gyrus or gyri (*TransvFP G*) located just dorsal, by the fronto-marginal sulcus (*FrontoM S*). Most of the ventral aspect of the frontal lobe (**d** ventral view of the cortical representation of the right hemisphere) is made by the orbital gyri subdivided by the "H-shaped" sulcus in lateral, medial, posterior and anterior orbital gyri. The gyrus rectus (G rectus) is a straight strip of cortex located at the junction of the medial and ventral aspects of the frontal lobe. It is medially limited from the orbital gyri by the olfactory sulcus (Olfact S). *Yellow indices* show interlobar sulci, whereas *white ones* show intralobar sulci/gyri

the superior tip of the parieto-occipital fissure and temporo-occipital notch/anterior occipital sulcus). Finally, the middle, or lateral occipital sulcus is located between them, into the middle occipital gyrus (Fig. 7a, b, e).

The superior occipital gyrus (O1) is a strip of cortex located between the dorsal edge of the hemisphere and the superior occipital sulcus (Fig. 7a, b, e). It continues the superior parietal lobule (P1) posterior to the level of the parieto-occipital fissure, and is medially continuous with the cuneus (O6) at the medial aspect of the brain without any distinct sulcal limit (Fig. 7e, g).

The superior temporal gyrus (T1), which runs from the inferior segment of the circular sulcus of the insula to the superior temporal sulcus, represents the temporal operculum (Fig. 7a, c, d). Its lateral aspect is posteriorly continued by the inferior parietal lobule (P2), at the junction

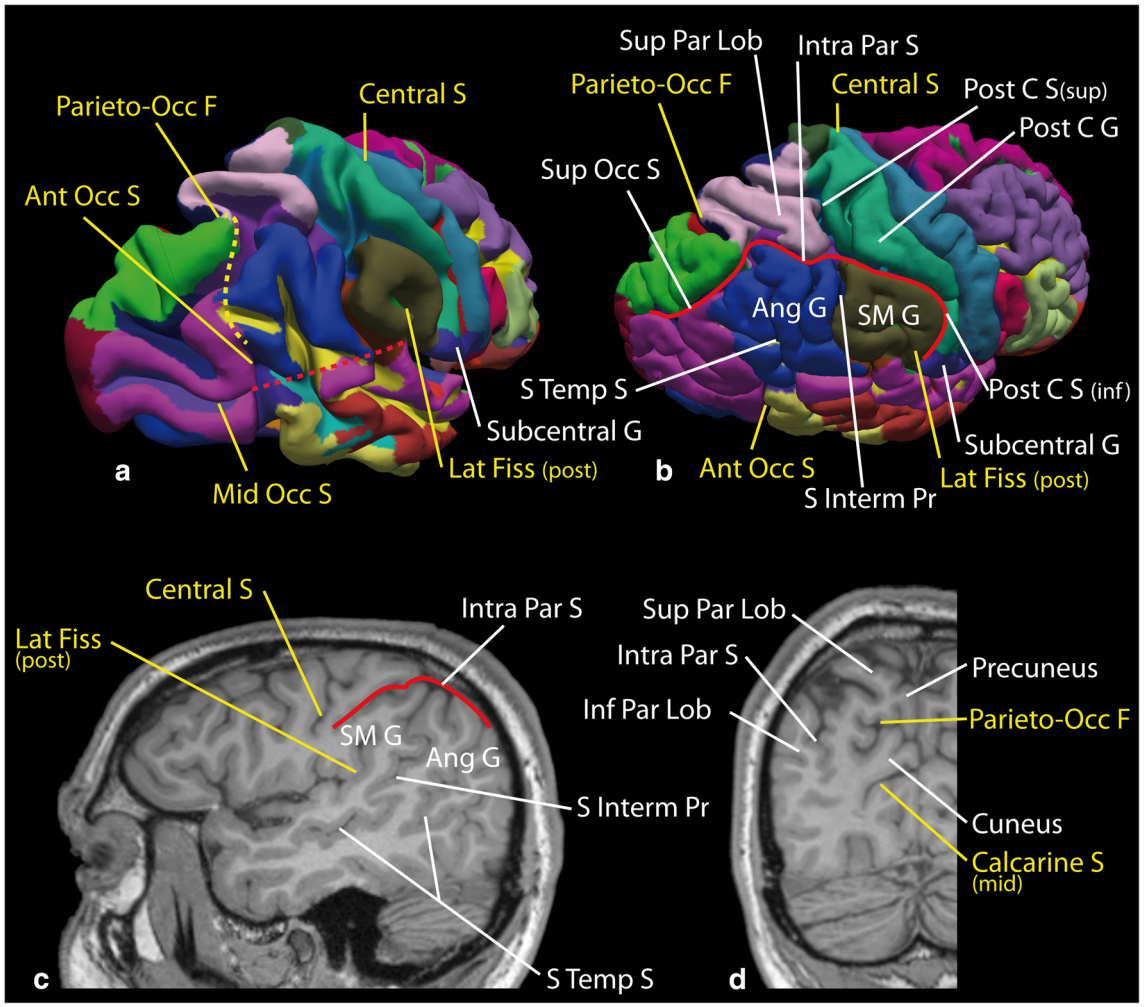
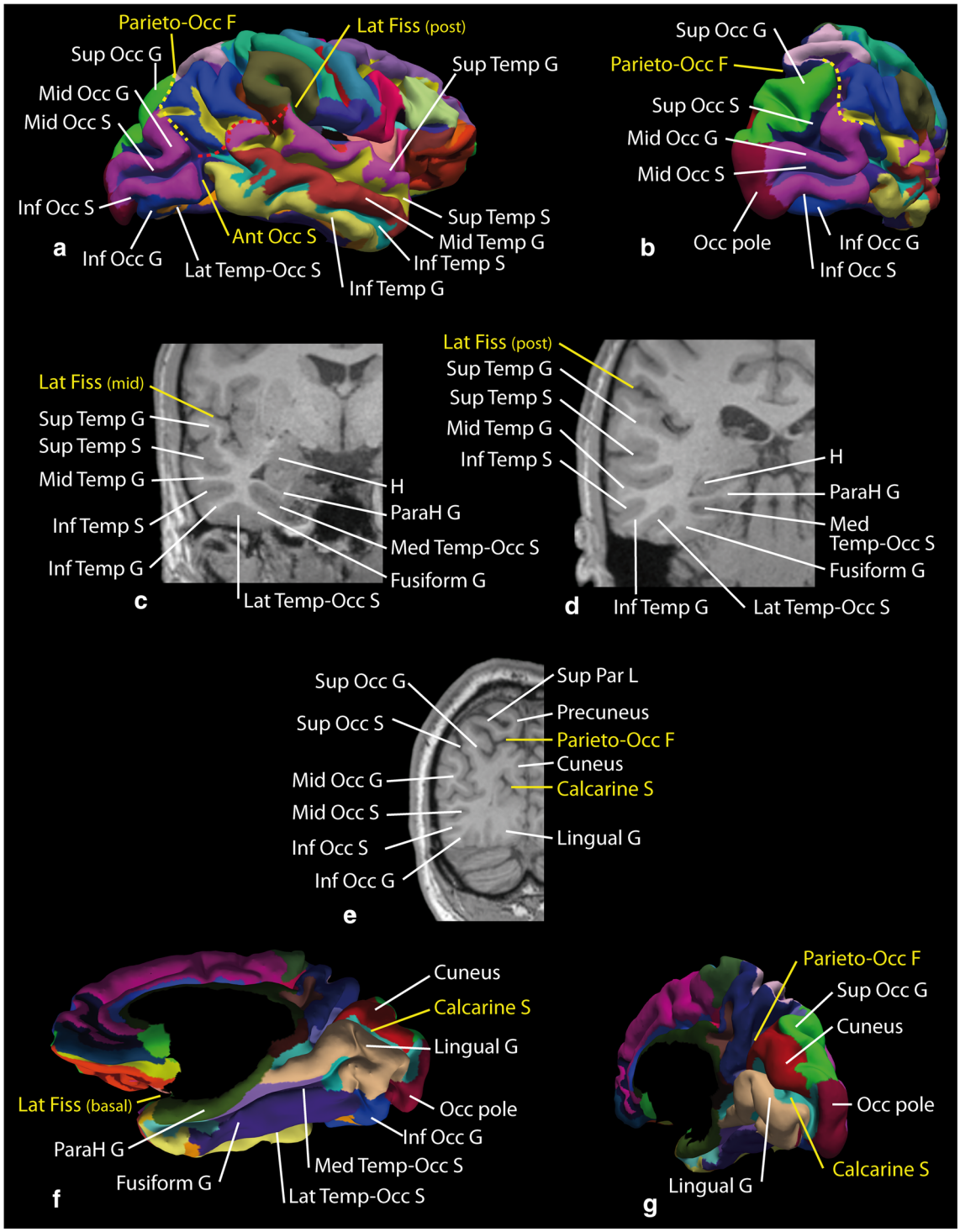


Fig. 6 Identification of the main sulci and gyri of the parietal lobe (lateral aspect). Laterally, the parietal lobe is only clearly limited from the frontal lobe by the central sulcus (*Central S*) anteriorly (**a** semi-inflated postero-lateral view of the right hemisphere). Its posterior limit to the occipital lobe (*yellow dotted line*) is a virtual line joining the superior tip of the parieto-occipital fissure (*Parieto-Occ F*) to the superior tip of the anterior occipital sulcus (*Ant Occ S*) or temporo-occipital incisura when the anterior occipital sulcus is missing. Its ventral limit from the temporal lobe (*red dotted line*) is also unclear and joins the point where the lateral fissure ascends posteriorly (*Lat Fiss post*), to the anterior tip of the middle (or lateral) occipital sulcus (*Mid Occ S*). A large ventrally curved sulcus divides the lateral aspect of the parietal lobe (*red continuous line* on **b** postero-lateral view of the right hemisphere and **c** sagittal section): it forms the inferior part of the postcentral sulcus (*Post C S*, *inf*), continued by the intraparietal sulcus (*Intra Par S*), itself continued by the superior occipital sulcus (*Sup Occ S*). The superior part of the postcentral sulcus (*Post C S*, *sup*) is usually independent from its inferior part, from which it continues the direction. These sulci limit the postcentral gyrus (*Post C G*, between the central and postcentral sulci), the superior parietal lobule (*Sup Par Lob* or *P1*, located dorsal to the intraparietal sulcus), and the inferior parietal lobule (*P2*) located ventral to the intraparietal sulcus. The inferior parietal lobule is further subdivided by a descending sulcus originating from the intraparietal sulcus, the sulcus intermedius primus (*S Interm Pr*): the supramarginal gyrus (*SM G*) is located anteriorly, around the posterior segment of the lateral fissure (*Lar Fiss*, *post*), whereas the angular gyrus (*Ang G*), located posteriorly, surrounds the posterior aspect of the superior temporal sulcus (*Sup Temp S*). On a coronal section (**d**), the intraparietal sulcus appears vertical. *Yellow indices* show interlobar sulci, whereas *white ones* show intralobar sulci/gyri

between the angular and supramarginal gyri. The superior aspect of T1 (Fig. 8a–d), which is the ventral bank of the lateral fissure, is a rather flat area interrupted by one or two transverse temporal gyri. On axial view (Fig. 8b), they form one or two cortical strips running antero-laterally from the posterior segment of the insula to the lateral aspect of the brain. They can easily be recognized on sagittal and coronal planes as small bulge(s), more or less resembling mushrooms (Fig. 8c, d). The transverse temporal gyrus/gyri split the superior aspect of T1 in planum temporale posteriorly and planum polare anteriorly (Fig. 8a–c).

The middle temporal gyrus (T2) is a straight cortical strip limited by the superior and inferior temporal sulci (Fig. 7a, c, d). It is continuous with the middle (or lateral) occipital gyrus (O2). The latter, which represents most of the lateral



aspect of the occipital lobe, is located between the superior and inferior occipital sulci and subdivided by the middle (or lateral) occipital sulcus (Fig. 7a, e). Similarly, the inferior temporal (T3) and occipital (O3) gyri are located along the ventral edge of the hemisphere, between the inferior temporal and occipital sulci dorsally, and the lateral temporo-occipital sulcus ventro-medially (Fig. 7a–g).

Ventro-basal aspect of the brain

Ventro-basal aspect: identification of interlobar sulci

The basal part of the lateral fissure forms a clear limit between the frontal and temporal lobes at the ventro-basal aspect of the brain (Fig. 5d). This is a large cleft joining the

◀**Fig. 7** Identification of the main sulci and gyri of the occipital and temporal lobes (lateral and ventral aspects). **a** **b** lateral and postero-lateral semi-inflated view of a right hemisphere, respectively. **c**–**e** coronal slices of a right hemisphere. **f**, **g** ventro-medial and postero-medial semi-inflated view of a right hemisphere, respectively. Limits of the temporal and occipital lobes (**a**, *yellow labels, red* and *yellow dotted lines*). The only clear limit of the temporal lobe is the lateral fissure (*Lat Fiss*). It is posteriorly continued by the parieto-temporal virtual limit, a line (**a** *red dotted*) joining the point where the lateral fissure ascends to the anterior tip of the middle occipital sulcus (*Mid Occ S*). The posterior limit of the temporal lobe is the occipito-temporal incisura, a small indentation sometimes continued by the anterior occipital sulcus (*Ant Occ S*) and by a virtual line (*yellow dotted* on **a**, **b** postero-lateral semi-inflated view of a right hemisphere) joining the superior tip of the anterior occipital sulcus to the supero-medial tip of the parieto-occipital fissure (*Parieto-Occ F*) at the superior edge of the hemisphere. No temporo-occipital limit exists at the ventral aspect of the brain. *The* lateral aspect of the temporal lobe (**a**, **c**, **d**) is subdivided into superior (*Sup Temp G*), middle (*Mid Temp G*) and inferior (*Inf Temp G*) temporal gyri by the superior (*Sup Temp S*) and inferior (*Inf Temp S*) temporal sulci. The superior temporal sulcus is usually easily recognized on coronal slices, whereas the inferior temporal sulcus, which is discontinuous, can be more difficult to localize. The lateral aspect of the occipital lobe (**a**, **b**, **e**) is half a cone subdivided by longitudinal sulci converging towards the occipital pole: the superior occipital gyrus (*Sup Occ G*) runs between the superior edge of the hemisphere and the superior occipital sulcus (*Sup Occ S*), which continues the intraparietal sulcus and usually ends posteriorly on a perpendicular sulcus. This configuration can easily be recognized on a coronal slice through the occipital lobe (**e**); the middle (or lateral) occipital gyrus (*Mid Occ G*) is limited by the superior (*Sup Occ S*) and inferior occipital sulci (*Inf Occ S*), the latter being not deep and running parallel to the inferior limit of the hemisphere (**a**, **b**, **e**). The middle occipital gyrus is the largest occipital one (**a**, **b**, **e**), longitudinally subdivided by the middle occipital sulcus (*Mid Occ S*); the inferior occipital gyrus (*Inf Occ G*), which is more or less continuous with the inferior temporal gyrus (*Inf Temp G*), is dorsally limited by the inferior occipital sulcus (*Inf Occ S*) and ventro-medially by the lateral temporo-occipital sulcus (*Lat Temp-Occ S*). *The* ventro-basal aspect of the occipital and temporal lobes is subdivided by two longitudinal temporo-occipital sulci (**f**, **g**): lateral (*Lat Temp-Occ S*) and medial (*Med Temp-Occ S*, or collateral). These sulci limit two temporo-occipital gyri forming two continuous strips of cortex: the lateral one, or fusiform gyrus (*Fusiform G*, O4–T4) is located between the inferior temporal sulcus and the lateral temporo-occipital sulcus. It usually does not reach the temporal nor occipital poles. The medial temporo-occipital gyrus (O5–T5) is subdivided into temporal and occipital parts without any clear limit (**c**, **d**): its temporal part, the parahippocampal gyrus (*ParaH G*, T5), is located between the medial temporo-occipital sulcus and the hippocampus; its occipital part, or lingual gyrus (*Lingual G*, O5) is limited by the medial temporo-occipital and the calcarine sulci. Since the fusiform gyrus does not reach the occipital pole, the inferior occipital and lingual gyri are contiguous posteriorly (**e**, **f**). *Yellow indices* show interlobar sulci, whereas *white ones* show intralobar sulci/gyri. Lat Fiss (basal): basal part of the lateral fissure

anterior perforated space to the limen insulae, along the posterior ridge of the lesser wings of the sphenoid bone. Conversely, no sulcus clearly limits the ventral aspect of the temporal and occipital lobes.

Ventro-basal aspect: identification of sulci and gyri

The orbital part of the frontal lobe (Fig. 5d) is a flat or slightly inferiorly concave area that surrounds the roof of the orbit. It is best explored on axial views, and contains two main sulci: (1) the olfactory sulcus that faces the olfactory tract and has a longitudinal course, a few millimeters from the midline; and (2) the H-shaped sulcus located laterally. The gyrus rectus forms the border between the medial and orbital aspects of the frontal lobe and is laterally limited by the olfactory sulcus. The orbital gyri form the rest of the orbital aspect of the frontal lobe and are subdivided into anterior, posterior medial and lateral parts by the H-shaped sulcus.

The ventro-basal part of the occipital and temporal lobes is subdivided by two longitudinal sulci, the lateral and medial temporo-occipital sulci (Fig. 7c, d, f). The medial temporo-occipital (or collateral) sulcus anteriorly reaches the temporal pole, whereas the lateral temporo-occipital sulcus is usually discontinuous and ends more posteriorly.

The lateral temporo-occipital or fusiform (T4–O4) gyrus is located between the lateral and medial temporo-occipital sulci. It is only present in the occipital lobe and posterior part of the temporal lobe, and has a characteristic triangular shape facing the floor of the middle cranial fossa on coronal views (Fig. 7d). The medial temporo-occipital gyrus (T5–O5) runs from the temporal to occipital poles, medial to the medial temporo-occipital sulcus. It may be divided into temporal (or parahippocampal gyrus, T5) and occipital (or lingual gyrus, O5) segments (Fig. 7f). The flat superior aspect of the parahippocampal gyrus, known as the subiculum, is continuous with the cornu ammonis of the hippocampus located dorsally.

Discussion and conclusion

Because image-guided surgery provides the neurosurgeon a great aid in localizing brain lesions during surgical procedures, precise anatomical localization of brain lesions in terms of sulcogyral anatomy sometimes seems outdated. It, nevertheless, remains important on a daily practice for a better communication between medical specialties (neuroradiologists, neurologists, neurosurgeons, neuroscientists): lesions are sometimes described in vague terms ("in the frontal lobe") that may additionally vary from one report to another. Having the same lesion described in different locations in various reports is of course a major source of confusion. Similarly, preoperatively describing a given lesion as pre- or post-central (as well as involving the supramarginal or the angular gyrus, the cuneus or the precuneus, etc.) would significantly modify the predicted

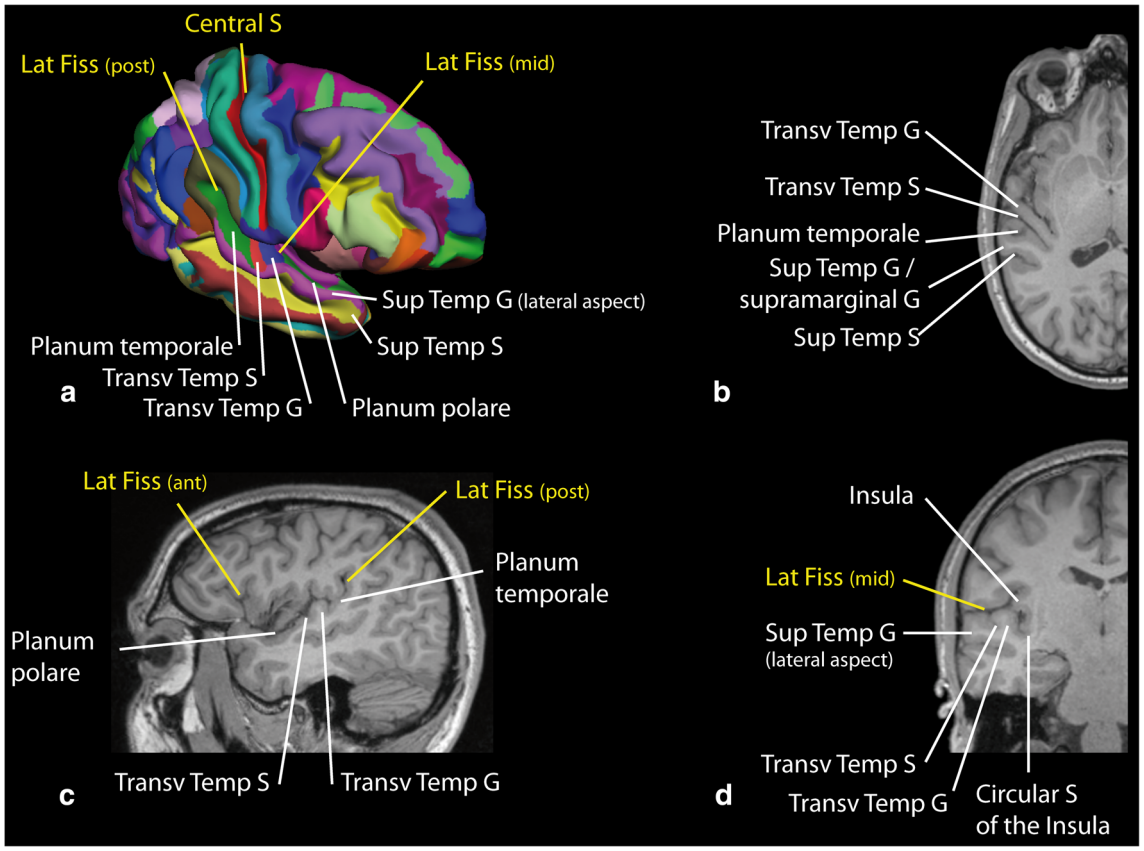


Fig. 8 Identification of the main sulci and gyri of the dorsal aspect of the temporal lobe. **a** semi-inflated antero–latero–dorsal view of a right hemisphere. **b** Axial, **c** sagittal, and **d** coronal slices of a right hemisphere. The superior aspect of the superior temporal gyrus (*Sup Temp G*, T1) is made of two flat areas limiting a bulged one (**a** antero–latero–dorsal view of a right hemisphere, **b** axial slice): the transverse temporal (*Transv Temp G*, or Heschl's) gyrus is running antero-laterally from the circular sulcus of the insula to reach the lateral aspect of T1. It is posteriorly limited by the transverse temporal sulcus (*Transv Temp S*) from a flat ascending area, the planum temporale. Anterior to the transverse temporal gyrus, the superior aspect of T1 is made of another flat area, the planum polare, which reaches the temporal pole. On axial (**b**) slices, the transverse temporal gyrus appears as an oblique strip of cortex, whereas on sagittal (**c**) or coronal (**d**) slices, it looks like a small mushroom, postero-laterally limited by the transverse temporal sulcus. *Yellow indices* show interlobar sulci, whereas *white ones* show intralobar sulci/gyri

consequences of the operative procedure; it would, thus, highly influence its planned resectability and, therefore, post-operative prognosis.

Using automated systems for sulcogyral identification is appealing, and multiple systems were proposed. Nevertheless, they usually rely upon more or less complicated algorithms taking several hours to provide a precise anatomical parcellation of the brain. For instance, the FreeSurfer packages include several brain atlases for both cortical (Desikan et al. 2006; Destrieux et al. 2010) and subcortical parcellations (Fischl et al. 2002). These methods unambiguously label every vertex of the brain using a Bayesian approach and brain atlases. This is one of the major available tools in the neuroimaging field but requires about 10 h to obtain the reconstruction of a segmented brain and brain surface. This is obviously not usable in a daily clinical practice. Moreover, the presence of a lesion or edema may be responsible for abnormal brain segmentation and may impose modified or additional procedures such as manual masking.

Being able to perform a manual sulcogyral segmentation in the vicinity of a brain lesion, thus, appears as a prerequisite for a good clinical practice. To be efficient (i.e., precise and not time-consuming), such a method has to use a simple set of rules systematically applied. This review did not aim to propose original rules, but to summarize and systematically organize them in a way usable in clinical practice.

This method relies upon three successive steps, namely the identification of the brain aspect, lobe and sulci/gyri bordering the lesion. It consists in localizing, on slices, large and simple structures first, then increasing the precision of this localization up to the sulcal/gyral level. This "concentric" approach is preferable to a direct one, which sometimes is closer to guessing than to a rational method.

Compliance with ethical standards

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 and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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

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