Journal of Clinical Neuroscience 21 (2014) 2219–2225

Contents lists available at ScienceDirect

Journal of Clinical Neuroscience

journal homepage: www.elsevier.com/locate/jocn

Neuroanatomical study

Brain sulci and gyri: A practical anatomical review

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ARTICLE INFO

Article history:
Received 26 December 2013
Accepted 23 February 2014

Keywords:
Anatomy
Brain
Gyri
Sulci
Surgery

ABSTRACT

Despite technological advances, such as intraoperative MRI, intraoperative sensory and motor monitoring, and awake brain surgery, brain anatomy and its relationship with cranial landmarks still remains the basis of neurosurgery. Our objective is to describe the utility of anatomical knowledge of brain sulci and gyri in neurosurgery. This study was performed on 10 human adult cadaveric heads fixed in formalin and injected with colored silicone rubber. Additionally, using procedures done by the authors between June 2006 and June 2011, we describe anatomical knowledge of brain sulci and gyri used to manage brain lesions. Knowledge of the brain sulci and gyri can be used (a) to localize the craniotomy procedure, (b) to recognize eloquent areas of the brain, and (c) to identify any given sulcus for access to deep areas of the brain. Despite technological advances, anatomical knowledge of brain sulci and gyri remains essential to perform brain surgery safely and effectively.

1. Introduction

According to international anatomical terminology, the brain is comprised of six lobes – frontal, parietal, occipital, temporal, insular and limbic [1]. For the purposes of this study, however, we will follow Yasargil's and Ribas's criteria that each brain hemisphere is comprised of seven lobes – frontal, central, parietal, occipital, temporal, insular and limbic [2,3]. Each lobe is made up of several gyri, which are separated from one another by sulci. A sulcus that is deep and continuous is commonly called a fissure, such as the Sylvian fissure. The term "lobe" defines a certain area of the brain separated from the rest, mostly by deep sulcus or fissures. It has no functional meaning but allows us to describe brain anatomy in comprehensive terms. Because sulci and gyri run horizontally in all the lobes but the central one, we prefer Yasargil's classification, which is easier to understand and apply during surgery.

Although brain structure and brain function are not strictly dependent on each other, studies show that they are closely related [3]. Hence, it is essential that every neurosurgeon should have a thorough knowledge of brain microanatomy, not only to understand neuroimages, but to be able to plan and conduct neurosurgical procedures [3]. Nevertheless, brain function varies a great deal between individuals and can be affected by pathology, for example, a slow growing mass within the parenchyma can, by means of neuroplasticity, change the location of relevant brain function allowing the surgeon to safely operate in "eloquent" areas. Neurophysiological testing in the operating room is essential in these kinds of cases but it is not always available, making anatomical landmarks useful tools.

Throughout the second half of the twentieth century, surgeons started to use fissures to approach extrinsic brain lesions, and sulci to access intrinsic lesions [1,4]. Once identified, brain sulci can be used as a microsurgical corridor or simply as an anatomical landmark [5,6]. Hence, thorough knowledge of the shapes and structures of the brain is essential to understand neuroimages, and proves crucial for image-guided procedures [3].

The aim of this paper is to show the threefold utility of anatomical knowledge of brain sulci and gyri, enabling the neurosurgeon to (a) localize the craniotomy procedure, (b) recognize eloquent areas of the brain, and (c) use any given sulcus to approach deep areas of the brain.

2. Methods

We studied 10 human adult cadaveric heads fixed in formalin and injected with colored silicone rubber to determine the relationship between surface osteometric landmark points (coronal

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http://dx.doi.org/10.1016/j.jocn.2014.02.024
0967-5868/

suture, lambdoid suture, squamous suture, and superior temporal line) and the sulci and gyri of the lateral aspect of the brain. A total of 20 hemispheres were analyzed, the distance between main bony landmarks and cerebral sulci was analyzed. Landmarks on the frontal bone were measured 3.5 cm from the coronal suture, landmarks on the temporal bone were measured 2 cm from the external acoustic channel.

3. Anatomical considerations

The lateral aspect of the brain is comprised of five visible lobes (frontal, central, parietal, occipital and temporal lobes) and a hidden area (the insula) (Fig. 1).

3.1. Frontal lobe

The frontal lobe borders on the precentral sulcus anteriorly and on the Sylvian fissure superiorly. It has two sulci (superior frontal and inferior frontal) and three horizontal gyri (superior frontal, middle frontal and inferior frontal). The inferior frontal gyrus is composed of three parts: the pars orbitalis (anteriorly), the pars triangularis (middle) and the pars opercularis (posteriorly). The pars opercularis of the inferior frontal gyrus in the dominant hemisphere (that is, the left hemisphere in most subjects) often includes the motor speech area commonly known as Broca's area.

From a surgical perspective, it is important to note that the three frontal gyri run horizontally as do the superior part of the squamous suture and the superior part of the superior temporal line. Hence, the relationships to be considered are as follows: the anterior ramus of the Sylvian fissure is located at the level of the squamous suture, the inferior frontal sulcus is located deep to the anterior aspect of the superior temporal line and the superior frontal sulcus is midway between the midline and the superior temporal line. Consequently, we can state that the superior frontal gyrus is located between the midline and a line that is equidistant to the midline and the superior temporal line, that the middle frontal gyrus is located between the superior temporal line and a line that is equidistant to the midline and the superior temporal line, and that the inferior frontal gyrus is located between the squamous suture inferiorly and the superior temporal line superiorly.

3.2. Central lobe

The central lobe is bounded by the precentral sulcus anteriorly, by the postcentral sulcus posteriorly, and by the Sylvian fissure inferiorly. It has one sulcus (central) and two vertical gyri (the precentral or motor, and the postcentral or sensory).

From a surgical perspective, it is important to note that the two gyri (precentral and postcentral) are vertical, like the coronal suture. The central sulcus – which borders on the precentral gyrus posteriorly – is variably located 2–5 cm behind the coronal suture, the longest distance between both structures occurring at the superior part, and the shortest near the Sylvian fissure. As the distance between the coronal suture and the central sulcus may vary, a more accurate way to locate the gyri of the central lobe is to use imaging to measure the distance from the coronal suture to the lesion requiring treatment [7,8].

The central sulcus presents three curves: the superior and inferior curves show a forward convexity, whereas the middle curve has a backward convexity. The middle curve resembles the shape of an inverted omega symbol, whereas the part of the gyrus located anteriorly to the middle curve corresponds to the hand's motor area and can be easily recognized through MRI [2].

3.3. Parietal lobe

The parietal lobe is bounded by the postcentral sulcus anteriorly, by the lateral parieto-temporal line posteriorly and, at the inferior aspect, by the posterior ramus of the Sylvian fissure anteriorly and the temporo-occipital line posteriorly. It has one sulcus

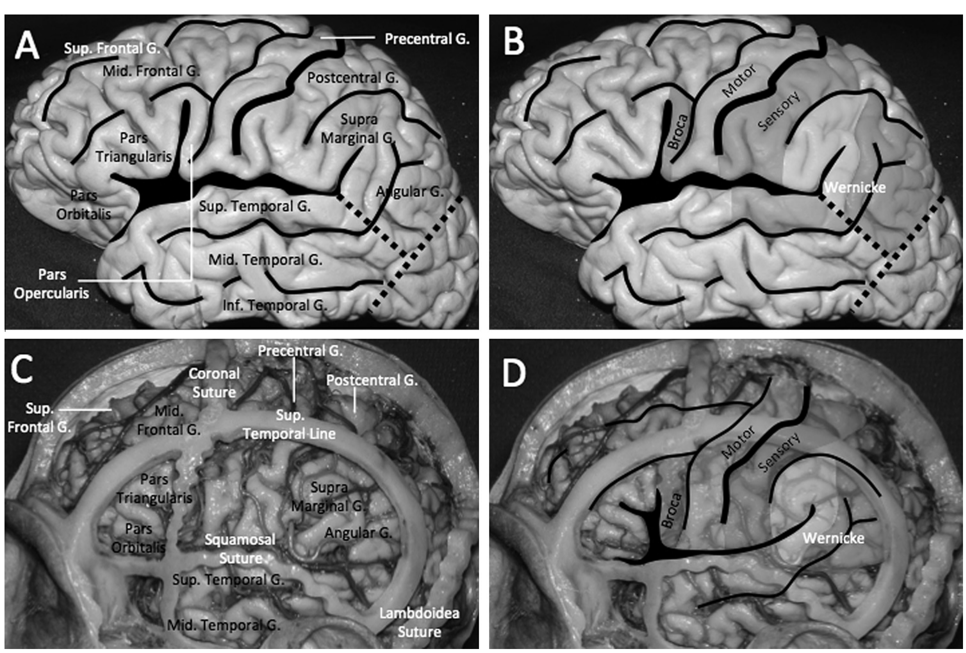

Fig. 1. Lateral aspect of the brain. (A) Sagittal view of the left hemisphere with the most significant sulci highlighted and the most important gyri named. The parietal, temporal and occipital lobes are separated by two lines – one which connects the superior end of the parieto-occipital internal fissure to the suboccipital notch (lateral parieto-temporal line) and one other which runs perpendicularly to the previous line, from the end of the Sylvian fissure to the lateral parieto-temporal line (temporo-occipital line). (B) Eloquent areas of the left hemisphere are colored as follows: red = Broca's area, green = motor strip, blue = sensory strip, yellow and purple = Wernicke's area, orange = language area. (C) Cerebral lobes and (D) eloquent areas of the left hemisphere are colored as in (B) to overlie surface osteometric landmark points (coronal suture, squamous suture, superior temporal line and lambdoid suture). G. = gyrus, Inf. = inferior, Mid. = middle, Sup. = superior.

(interparietal) and two parts called lobes (the superior parietal and the inferior parietal). The inferior parietal lobe is comprised of two gyri: the supramarginal gyrus (around the end of the Sylvian fissure) and the angular gyrus (around the end of the superior temporal sulcus). Additionally, the supramarginal and angular gyri in the dominant hemisphere (most commonly, the left side) frequently contain the speech sensory area commonly known as Wernicke's area.

From a surgical perspective, it is important to know that the interparietal sulcus is located at the level of the superior temporal line (mean distance 1.2 ± 0.8 cm, 95% confidence interval [CI]). Hence, it can be said that the superior parietal lobe is located between the midline and the superior temporal line, whereas the inferior parietal lobe, together with the supramarginal and angular gyri, is to be found between the superior temporal line and the squamous suture.

3.4. Occipital lobe

The occipital lobe is bounded anteriorly by the lateral parieto-temporal line, which runs from the superior end of the internal parieto-occipital sulcus to the suboccipital groove. The lateral surface of the occipital lobe presents no specific sulci or gyri, and unlike the internal aspect, the external aspect of the occipital lobe is not an eloquent area.

From a surgical perspective, it is important to know that the lateral parieto-temporal line is located at the level of the lambdoid suture. Therefore, it can be stated that the occipital lobe is located posterior to the lambdoid suture.

3.5. Temporal lobe

The temporal lobe is bounded by the Sylvian fissure superiorly, and by the temporo-occipital and the lateral parieto-occipital lines posteriorly. As in the frontal lobe, the lateral aspect of the temporal lobe has two sulci (the superior temporal and the inferior temporal) and three horizontal gyri (superior temporal, middle temporal and inferior temporal).

From a surgical perspective, it is important to know that, as mentioned above, the Sylvian fissure is located at the level of the squamous suture. Additionally, the floor of the middle cranial fossa, where the lateral surface of the temporal lobe ends, is located at the level of the upper border of the zygomatic arch. It can thus be stated that the superior temporal gyrus is located immediately below the squamous suture, whereas the inferior temporal gyrus is immediately above the zygomatic arch, and the middle temporal gyrus is equidistant to the squamous suture and the zygomatic arch.

3.6. Sylvian fissure and insula

The Sylvian fissure is the only sulcus in the lateral aspect of the brain that is easily identified on the surface. It is the most commonly used sulcus in neurosurgery; however, it is anatomically very complex. It is represented as a container and its contents. The opercula (frontal operculum, central operculum, parietal operculum and temporal operculum) and the insula function as an outer and inner container, that is, they encase their contents outwards and inwards, respectively.

For the purposes of this study, the insula is considered as a lobe. It has an anterior wall, which is small and practically unknown, and a lateral wall, which includes the short and long gyri.

Superficially to deeply, the Sylvian fissure comprises three parts: a superficial section (arachnoid), a middle section (opercular) and a deep section (insular). The anterior superficial part (arachnoid) in its lateral aspect comprises three rami: the horizontal anterior ramus, the anterior ascending ramus and the posterior ramus. The anterior two rami divide the inferior frontal gyrus into the above mentioned parts: the pars orbitalis, the pars triangularis, and the pars opercularis.

4. Surgical considerations

Practical knowledge of the anatomy of brain sulci and gyri serves a threefold purpose: (a) to localize a craniotomy procedure,

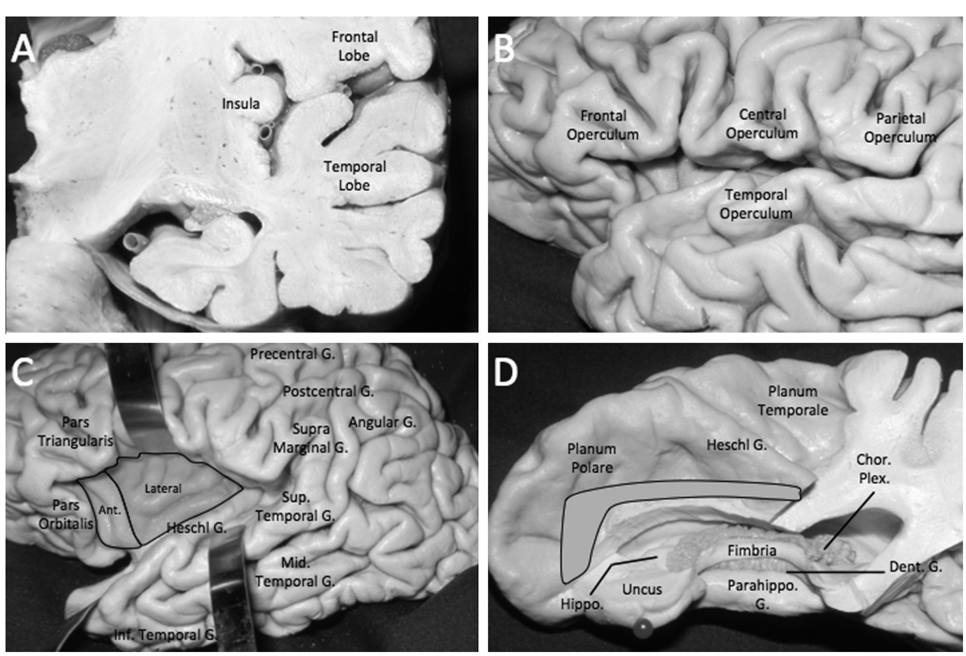

Fig. 2. Temporal lobe, Sylvian fissure and insula. (A) Coronal view of a left temporal lobe. (B) Lateral view of a left Sylvian fissure. (C) The Sylvian fissure has been opened to fully expose the insula (green = anterior region, pink = lateral region). (D) Representation of the insula (yellow) in the temporal lobe. Chor. Plex = choroid plexus, Dent. = dentate, G = gyrus, Hippo. = hippocampus, Inf. = inferior, Mid. = middle, Sup. = superior.

(b) to recognize eloquent areas of the brain, and (c) to use any given sulcus to approach deep areas of the brain (Fig. 2–4).

4.1. Craniotomy location

It is important to remember the relationships among the brain sulci and gyri and the surface osteometric landmark points. The lateral aspect of the brain has two horizontal landmarks (the superior temporal line and the squamous suture) and two other essentially vertical landmarks (the coronal suture and the lambdoid suture). In this way, the superior temporal line and the squamous suture help to locate horizontal sulci and gyri, whereas the coronal and the lambdoid sutures are useful to locate vertical sulci and gyri.

Horizontal landmarks afford a more precise localization than vertical ones. For this reason, horizontal gyri are more accurately located by means of the approaches stated in Table 1.

Vertical landmarks are more variable; therefore, it is necessary to rely on an additional method to approach them. Vertical gyri include the precentral and the postcentral gyri. As we know that the coronal suture can be 2–5 cm from the central sulcus and that this landmark is not completely reliable, the problem can be solved by measuring the distance between the coronal suture and the lesion based on the information obtained from an MRI or CT scan, and transferring these measurements to the patient's skull.

4.2. Recognizing eloquent areas

Eloquent areas of the brain's lateral aspect will depend on whether the hemisphere is non-dominant (motor strip and sensory strip) or dominant (the speech area is added) (Fig. 1C, D). As mentioned in the introduction, anatomical landmarks cannot be used as the sole element to recognize eloquent areas but should be complemented with intraoperative neurophysiological testing. The

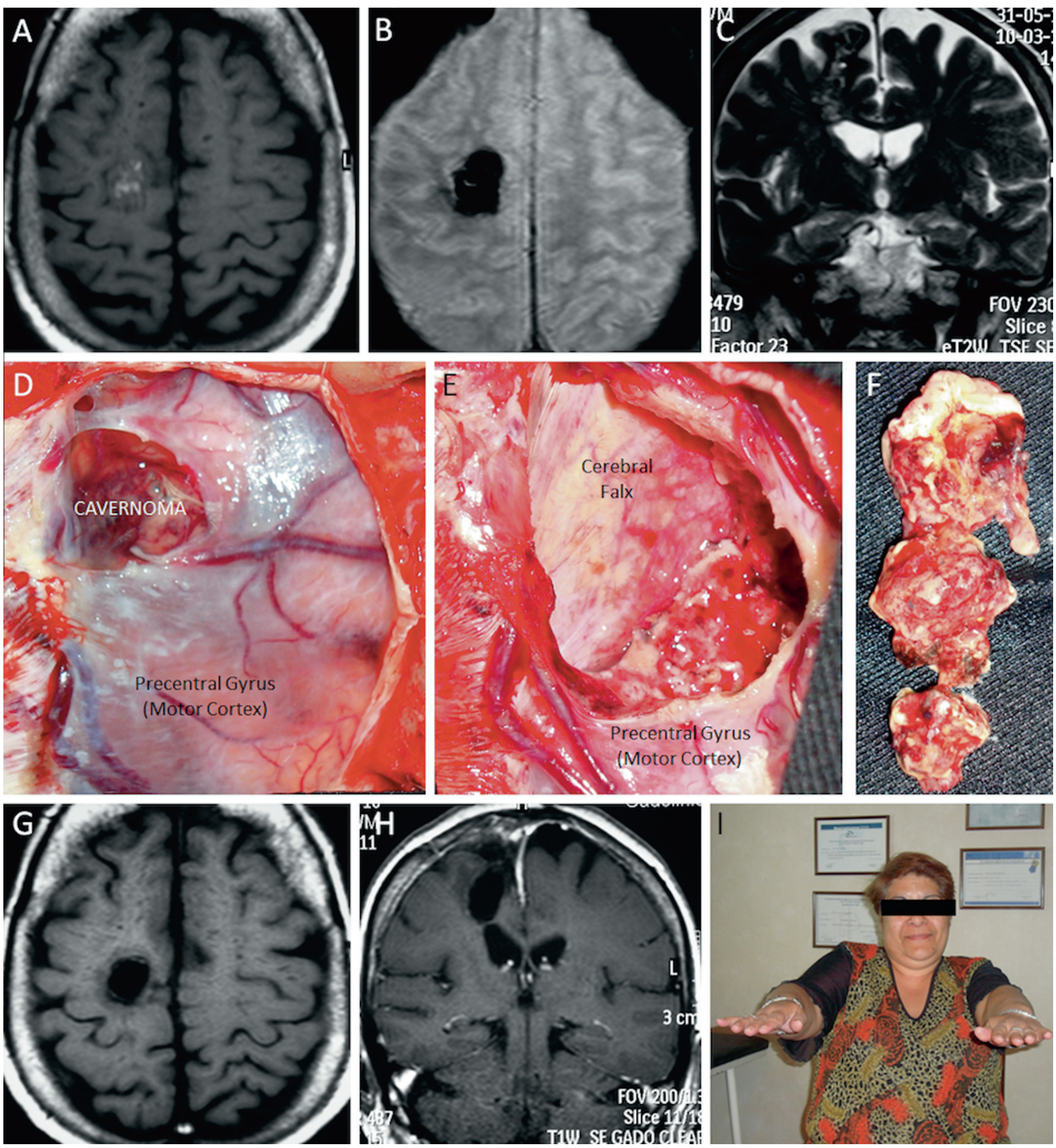

Fig. 3. Patient with a cavernoma in the superior frontal gyrus of the right hemisphere, immediately behind the precentral sulcus. Preoperative (A) axial fluid attenuated inversion recovery (FLAIR), (B) axial gradient echo and (C) coronal T2-weighted MRI. A nodular lesion hyperintense on T2-weighted and FLAIR imaging, rich in iron, can be seen occupying the posterior aspect of the superior right frontal gyrus, which can be identified by its posterior limit with the precentral sulcus. (D) Exposed lesion (superior view). (E) Brain photograph after cavernoma resection. (F) Photograph of the resected cavernoma. Postoperative (G) axial FLAIR and (H) T1-weighted coronal MRI showing resection of the lesion. (I) Patient postoperatively showing no motor deficit. (This figure is available in colour at www.sciencedirect.com.)

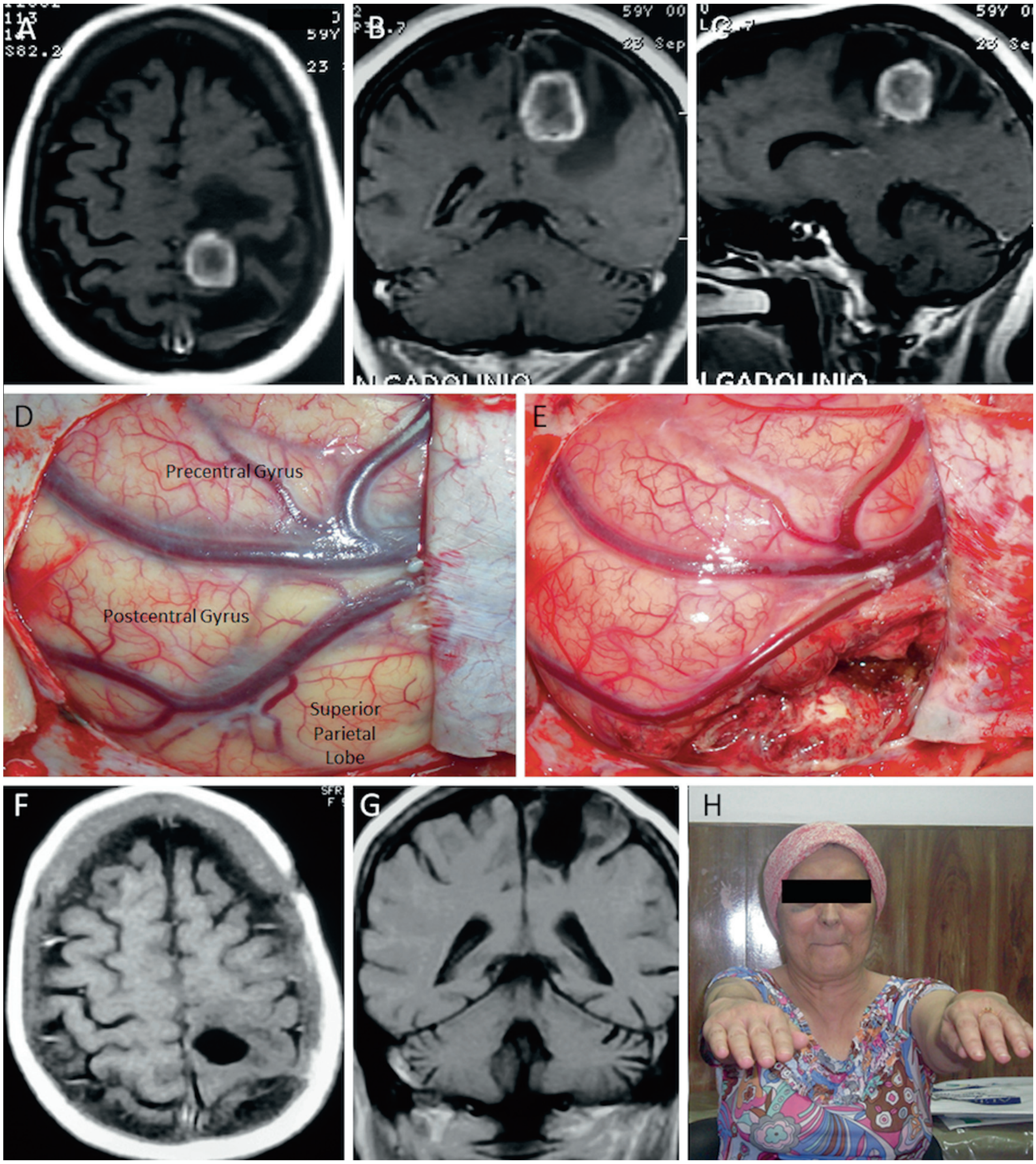

Fig. 4. Patient with breast cancer metastasis in the superior part of the left central lobe (motor and sensory strips). Preoperative T1-weighted contrast enhanced (A) axial, (B) coronal and (C) sagittal MRI show the lesion (D) Exposed brain after the dura was opened and (E) after tumor resection. Postoperative (F) axial and (G) coronal T1-weighted MRI showing resection of the lesion. (H) Patient postoperatively showing no motor deficit. (This figure is available in colour at www.sciencedirect.com.)

position of eloquent areas may vary a great deal between people and can be affected by the pathology. The following is a review of common anatomical landmarks associated with important cerebral functions, and while not enough to perform safe operations they still have great value in neurosurgical planning. However, with increasing knowledge of brain function, fewer areas are labelled as "silent" and we are becoming increasingly aware that resection of any brain structure may produce some damage, even if we cannot see it in routine evaluation.

Motor strip: precentral gyrus. As displayed on axial MRI, it is located anterior to the omega sign.

Sensory strip: postcentral gyrus. As displayed on coronal MRI, it is located posterior to the omega sign.

Broca's area (speech production): pars opercularis of the inferior frontal gyrus. It is located in the inferior frontal gyrus, posterior to the ascending frontal ramus of the Sylvian fissure. This area is lateral to the foramen of Monro.

Wernicke's area (language comprehension): supramarginal and angular gyri. This area is located laterally to the ventricular atrium.

4.3. Approaching deep lesions through sulci

After pterional craniotomy, the Sylvian fissure should be the chosen path to approach the basal cisterns. However, here we suggest that other sulci could be also used to approach deep intra-axial lesions. In this way, any sulci of the brain's lateral aspect can eventually provide access to deep areas. When using sulci to approach deep lesions the underlying white matter function always has to be considered and major subcortical pathways should be treated with the same care as eloquent cortical regions.

Table 1
Approaches to accurately locate the horizontal gyri

Superior frontal gyrus	Between the midline and the frontal equidistant line
Middle frontal gyrus	Between the frontal equidistant line and the superior temporal line
Inferior frontal gyrus	Between the superior temporal line and the squamous suture
Superior parietal lobe	Between the midline (sagittal suture) and the superior temporal line
Inferior parietal lobe	Between the superior temporal line and the squamous suture
Superior temporal gyrus	Immediately inferior to the squamous suture
Middle temporal gyrus	The gyrus center is located at the level of the equidistant temporal line
Inferior temporal gyrus	Immediately superior to the zygomatic arch

5. Discussion

Despite the interest in neuroanatomy and the description of brain hemispheres made by Vesalius, Sylvius and Willis, the first scientist to develop a reasonable description of the sulci and gyri patterns was Gratiolet. Until then, interpretations of the anatomy of the brain had been chaotic, some of them even comparing sulci and gyri with loops of the small intestine. His studies were followed by Broca's, which presented both a structural and a functional order whereby each piece of the structure correlated functionally with another [2].

In broad terms, it can be argued that the lateral aspect of the brain is comprised of six horizontal gyri (three frontal and three temporal), two vertical gyri (the pre and postcentral), two square areas (the superior parietal lobe and the inferior parietal lobe), and one triangular region (the occipital lobe). Thorough knowledge of brain microanatomy is a crucial tool for neurosurgeons when it comes to planning and performing neurosurgical procedures. This has been proved particularly true since the advent of imaging studies, which allow surgeons to anticipate very fine details of the relationship between the lesion to be managed and the normal anatomy, so that a surgical strategy can be developed to approach and address the medical condition without having to disrupt normal brain functions [9].

Knowledge of the sulci and gyri anatomy provides the surgeon with several elements to plan procedures. Firstly, it enables the surgeon to define the surgical approach to be used and to delimit the craniotomy, and should be considered regardless of the availability of neuronavigation in the operating room, most importantly because anatomical parameters facilitate an accurate approach to brain structures [10,2,11]. Knowledge of the relationship between the osseous elements and the sulci and gyri described in this study allows surgeons to accurately anticipate which structures underlie the skull and should be focused on. Secondly, sulci and fissures can be used as access routes to reach deep lesions, thereby reducing the need to perform a corticotomy and to operate through the normal parenchyma; nevertheless subcortical white matter pathways should be treated with the same care as the cerebral cortex in order to preserve functional tissue [12]. Thirdly, a relationship is known to exist between brain structure and brain function, so knowledge of this relationship allows the surgeon to define which intraoperative monitoring techniques (such as electrocorticography) may be necessary, and to anticipate which area of the lesion is in close contact with brain eloquent areas. In a recent review by Pouratian and Bookheimer the authors state that even patients with lesions compromising eloquent areas can be safely operated by using intraoperative neurophysiological testing and that patients should not be excluded from surgery just on an anatomical basis [9]. In fact, Lubrano et al. were able to securely remove gliomas from anatomical eloquent areas (Broca's area) without producing any postoperative speech deficits [13]. The fact that a great anatomo-functional variability has extensively been demonstrated underlines that anatomy cannot be used as the sole factor to base neurosurgery on or decide if a lesion can be safely removed.

Anatomical knowledge is a crucial roadmap for the surgeon while surgery is being performed. In fact, this applies irrespective of the availability of a neuronavigator or electrophysiological monitoring. The appropriate three-dimensional knowledge of the anatomy plus a sense of "X-ray vision" constitutes the pillars of any neurosurgical procedure [14]. The former enables the surgeon to anticipate how a given lesion may have disrupted the normal anatomy of the brain and to preserve key functional elements, whereas the latter is necessary to know which structures beyond the surgeon's view may be affected by the lesion and, potentially, by the surgical procedure. Additionally, with the background knowledge obtained from imaging, this "see-through vision" enables the surgeon, by using surface anatomical landmarks, to reach lesions which would otherwise go unnoticed because they are not visible on the brain cortex [15]. These issues are relevant irrespective of the availability of a neuronavigator, which may be crucial to delimit the surgical approach, define craniotomy extension and locate deep lesions, but does not replace the surgeon's three-dimensional microanatomical vision when it comes to approaching the medical condition in the operating room [1,4,16,17]. This type of technology is costly and not all operating rooms are fitted with the equipment, particularly in developing countries, where anatomical knowledge can take on special relevance. Another important issue connected with neuroanatomy is the neurosurgeon's training, especially during residency and the first years of surgical practice, when normal anatomy should be studied with special emphasis, since it will be the neurosurgeon's fundamental support both in surgical planning and practice.

Thorough knowledge of supratentorial sulci and gyri as well as their relationship with the calvaria is useful to determine intracranial resection strategies and approaches. Thorough knowledge of three-dimensional anatomy and the ability to "see through" the normal parenchyma allow surgeons to approach lesions safely, even without neuronavigation. Additionally, anatomical knowledge is essential for the training and professional development of neurosurgery residents around the world. However, while knowledge of both cortical and subcortical anatomy is essential, it is not sufficient: brain function should also be studied at the individual level to optimize the results of cerebral surgery.

Conflicts of Interest/Disclosures

The authors declare that they have no financial or other conflicts of interest in relation to this research and its publication.

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