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RESEARCH REPORT

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Sulci and gyri are topological cerebral landmarks in individual subjects: a study of brain navigation during tumour resection

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Abstract

Surgical resection of brain tumours aims at the maximal safe resection of the pathological tissue with minimal functional impairment. To achieve this objective, reliable anatomical landmarks are indispensable to navigate into the brain. The neuronavigation system can provide information to target the location of the patient's lesion, but after the craniotomy, a brain shift and relaxation mismatch with it often occur. By contrast, sulci/gyri are topological cerebral landmarks in individual patients and do shift with the brain parenchyma during lesion removal, but remain independent from brain shift in relation to the sulci/gyri. Here, we present a case report of a novel strategy based on anatomical landmarks to guide intraoperative brain tumour resection, without using a standard neuronavigation system. A preoperative brain mapping of the peri-tumoural sulci by the MRI and surface reconstruction was followed by confirmation of the anatomical landmarks for the motor cortex using navigated transcranial magnetic stimulation. The resulting location was used as a seed for diffusion tensor imaging tractography to reconstruct the corticospinal tracts. These selected cortical landmarks (sulci/gyri) delimited the margins of the two lesions and the specific location under which the corticospinal tract courses, thus facilitating monitoring of the peri-tumoural region during brain resection. In this case, 96% of the brain tumour from the pericentral somatomotor region was successfully removed without chronic post-operative motor impairments. This approach is based on cortical anatomy that is fixed during surgery and does not suffer from the brain shift that could misplace the lesion according to the neuronavigation system.

KEYWORDS
brain navigation, gyrus, neuroanatomy, neurosurgery, sulcus

1 | INTRODUCTION

To approach resection of a lesion, the neurosurgeon requires reliable anatomical landmarks to navigate into the brain, and these can be provided by pre-surgically acquired magnetic resonance imaging (MRI). In the operating room, the neurosurgeon can use a neuronavigation system to relate structural images of the patient's brain that provide important information regarding the location of lesions. The neuronavigation system synchronises the preoperative MRI in axial, coronal and sagittal planes of the brain to the scalp of the patient. During surgery, positioning the probe on the scalp of the patient can provide useful information to target the location of the patient's brain lesion. It allows recognition of those lesions that are not immediately visible on the surface of the brain and, thus, permits the surgeon to approach also deep brain lesions. Nevertheless, after the craniotomy has been made, a brain shift and relaxation mismatch with the neuronavigation system usually occur, especially at the later stages of surgical resection (Wang & Song, 2011). To overcome this limitation, an MRI, a CT scan or an ultrasound (Shi et al., 2021) must be reobtained during surgery for a real-time intraoperative tumour location based on real-time image guidance. However, these specific and dedicated tools can be very expensive and not easily available in an operating room. The most promising of these tools may be intraoperative ultrasound because of its relatively low cost and lack of radiation exposure, but ultrasound, as in the case of intraoperative MRI and CT scan, produces interruptions during brain surgery, and, in addition, small lesions are difficult to detect, and blood and haemostatic agents within the operative region can create problems in image interpretation (see Bal et al., 2016). Improvements in image resolution, probe features and image analysis will overcome these difficulties in the future. Here, we report an approach that does not require real-time image guidance tools during brain surgery but relies on critical sulcal landmarks obtained from the preoperative MRI.

Based on the known relations of the sensorimotor representations with certain sulci and gyri of the brain, one can predict the locus of a specific body part in the pericentral cortical region. This prediction can be tested preoperatively by navigated transcranial magnetic stimulation (nTMS) and then confirmed, intraoperatively, using direct cortical stimulation (DES) to elicit the contraction of the predicted muscle group and record the motor activity by means of electromyography. This sensorimotor activity can also be obtained in an anaesthetized patient. Thus, anatomical localization of the sensorimotor cortical areas provides the neurosurgeon with reliable landmarks for brain navigation. Once the central sulcus has been determined, the adjacent sulcal and gyral patterns can be used as landmarks for the overall brain navigation.

The aim of the present report was to demonstrate the usefulness of surface brain landmarks (sulci/gyri) to navigate intraoperatively during the neurosurgical operation and facilitate the identification of lesion location and possible specific brain functional regions associated with specific sulcal/gyral patterns. These intrinsic landmarks for brain navigation in individual patients can be obtained from the preoperative brain MRI scan and from the surface reconstruction of it that permits accurate matching with the sulci and gyri under direct vision in the exposed brain during surgery. In this case report, a method is presented for pre-surgical planning that provides the neurosurgeon with a detailed map of the location of the lesion in relation to the sulci and gyri that can be viewed during surgery. This map can be overlaid on the exposed brain during surgery providing constant landmarks for navigation in the operative brain region.

2 | MATERIALS AND METHODS

Patient: We investigated an adult patient with a brain tumour that was not visible from the cortical surface in the fronto-parietal region of the left hemisphere. The MRI demonstrated that the tumour was located at a minimum distance of 5–10 mm below the cortical surface. The patient provided written informed consent for publication of the clinical data, according to the local ethics committee (Comitato Etico Messina, AOU Policlinico G. Martino 480-21Bis).

2.1 | Preoperative planning

2.1.1 | MRI acquisition

The patient underwent a preoperative brain scan in a 1.5-T MRI (Achieva 1.5T, Philips Medical Systems, The Netherlands). A specific MR acquisition protocol was used, including the following sequences: T1-weighted, gadolinium-enhanced multiplanar reconstruction (MPR) (TR/repetition time = 8.1, TE/echo time = 3.7); 3D FLAIR-VISTA/fluid attenuated inversion recovery volumetric isotropic T2w acquisition (TR = 8000, TE = 331.5/7 slice 1 mm); diffusion-weighted sequences (DWI with 32 directions of gradients, with 80 slices for each direction; FS = 1.5, TR = 2383.9, TE = 51.9) for diffusion tensor imaging (DTI) computation. The T1-weighted gadolinium enhanced MPR sequence was the reference anatomical MR scan for the pre-operative navigated transcranial magnetic stimulation (nTMS) motor mapping and for the DTI computation and tractography; conversely, the 3D FLAIR-VISTA sequence was used for the surface reconstruction of the patient's brain to identify cerebral sulci before and during surgery.

2.1.2 | Brain surface reconstruction

Any volumetric brain MRI sequence can be used to delete non-brain tissue from an image of the whole head applying the freely available software Brain Extraction Tool (BET; Smith, 2002). Based on the brain images obtained with BET software, a surface reconstruction of the brain can be provided using the interactive program MANGO (http://ric.uthscsa.edu/mango/download.html). In addition, MANGO allows for the simultaneous visualization of the movement of the cursor on the screen within the three planes (i.e. axial, coronal and sagittal) of the MRI. Importantly, the movement of the cursor can also be viewed simultaneously on the surface reconstruction of the same brain (Figure 1a).

2.1.3 | Mapping of the relevant sulci and gyri

The sulci of interest were drawn on the reconstructed brain surface based on the brain MRI of the patient (Figure 1a). The characteristic hand knob (i.e. the hand motor region) within the central sulcus was identified as reported by Yousry et al. (1997) and Germann et al. (2020). The central sulcus was marked on the brain surface reconstruction, and the gyri and sulci in the peri-tumoural region of interest (ROI) were identified and labelled by using the Atlas of the Morphology of the Human Cerebral Cortex on the Average MNI Brain (Petrides, 2019; Figure 1b).

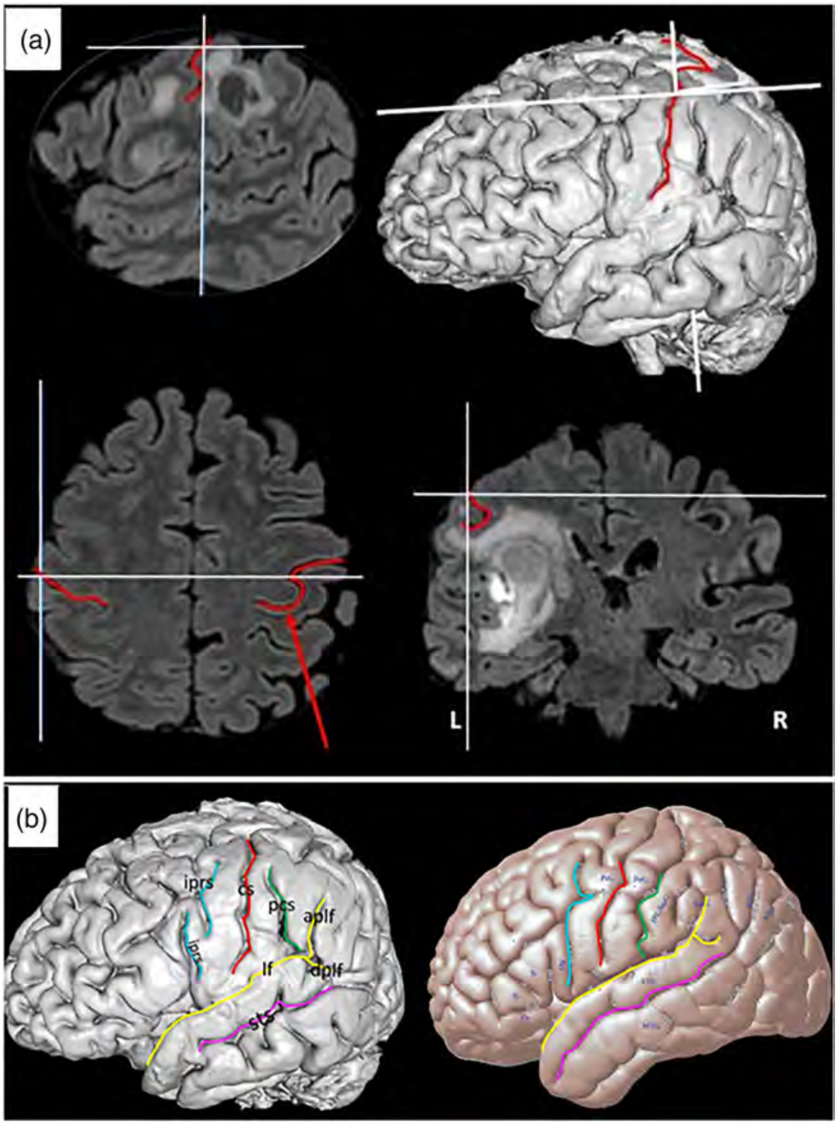

FIGURE 1 (a) Surface reconstruction of the MRI of the left hemisphere of the patient (top right side) with axial, coronal and sagittal planes (left side) to show the location of the brain tumour below the cortical surface. The white cross-points indicate the same cursor positions on the sections and on the cortical surface reconstruction of the left hemisphere of the brain. The red lines indicate the central sulcus. The central sulcus is identified on the surface reconstruction by the hand knob detected on the axial plane within the central sulcus (red arrow) in the right hemisphere and a red outline in the left hemisphere of the brain. The brain tumour, which lies below the cortical surface, can be seen in the coronal and sagittal sections. The critical region is represented by the unaffected white matter that extends posterior to the central sulcus. L, left hemisphere; R, right hemisphere. (b) In addition to the central sulcus (see Figure 1b), other relevant sulci are identified on the brain of the patient (left panel) based on the sulci on the average MNI brain (right panel; Petrides, 2019, with Elsevier permission). *aplf*, ascending posterior ramus of the lateral fissure; *cs*, central sulcus; *dplf*, descending posterior ramus of the lateral fissure; *iprs*, inferior precentral sulcus; *lf*, lateral fissure; *pcs*, post-central sulcus; *sts*, superior temporal sulcus

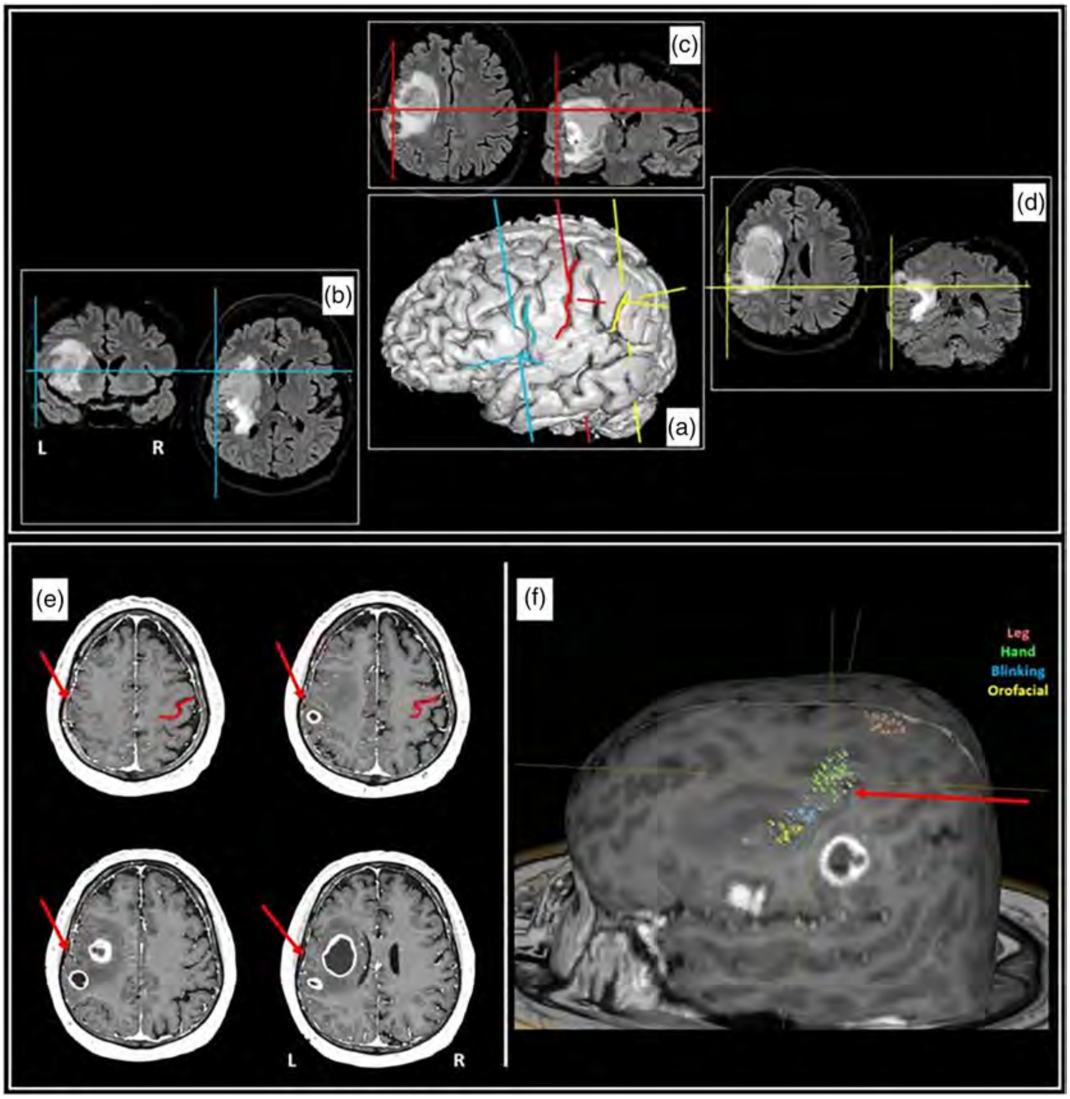

FIGURE 2 Upper panel. The anterior and posterior limits of the lesions. (a) Surface reconstruction of the brain of the patient: The blue line indicates the anterior border of the lesions, the red line the central sulcus, and the yellow line the ascending posterior lateral fissure, that is, the posterior limit of the lesions. (b) Axial and coronal views of the anterior limit of the lesion, which is located at the level of the precentral sulcus (blue lines). (c) Axial and coronal section at the level of the central sulcus (red lines). (d) Axial and coronal sections of the posterior border of the lesions at the level of the ascending posterior lateral fissure (yellow lines). Each coloured cross indicates, respectively, the same anatomical position. Note that, on the cortical surface reconstruction, it is not possible to localize the tumour that extends from the inferior precentral sulcus (blue lines) as far as the ascending posterior ramus of the lateral fissure (yellow lines). Lower Panel. (e) nTMS map of the motor cortex on the precentral gyrus; axial view of the patient's MRI to show the hand knob (red outline) on the contralateral unaffected hemisphere. (f) The 3D rendering using the Nexstim NBS system of the patient MRI: The coloured dots represent the positive points of the induced motor evoked potentials (MEPs). Brown indicates the leg region, green the hand region, blue the blinking region, and yellow the orofacial region

2.1.4 | Motor evoked potentials (MEPs) via nTMS to confirm the motor cortical region in relation to the morphology of the central sulcus

Preoperative mapping of the motor cortex on the pericentral sulcal region (precentral and post-central gyri) was performed using the Nexstim NBS system 4.3 (Nexstim Oy, Elimäenkatu 9 B, Helsinki, Finland). The MEPs through nTMS were examined before surgery. The patient's head and the reference anatomical MRI were co-registered using anatomical landmarks and surface registration (Conti et al., 2014). A single-pulse stimulation paradigm was applied using a figure-of-eight coil over the patient's scalp. The coil was moved over the patient's precentral motor cortex to confirm the mapping of the relevant sulci and gyri. The single nTMS pulse elicited the expected MEP motor response on the corresponding contralateral muscles. Electrodes positioned on the patient's body for the recording of MEPs were placed on the orofacial (orbicularis oris [ORB]), hand (first digital interosseous [FDI]) and leg (tibialis anterior [TA]) muscles; for the procedure, see Raffa et al. (2018, 2019) (Figure 2a, upper panel).

2.1.5 | Image fusion and DTI somatotopic tractography of the corticospinal tract

DWI sequences were imported together with the nTMS map of the motor cortex and with the anatomical reference MRI into the neuronavigation system for computing the DTI tensor. Once the tensor was calculated, the software created the Apparent Diffusion Coefficient (ADC) map and the Directionally Encoded Color map. The Directionally Encoded Color map was used to select the ROI for the tracking of the corticospinal fibre tract in the hemisphere affected by the tumour. A multiple-ROI technique was used for this 'somatotopic' DTI tractography. The first ROI was the anterolateral portion of the ipsilateral cerebral peduncle, and the second ROI was the motor MEP map corresponding, respectively, to the motor representation of the contralateral ORB, FDI and TA muscles. Then, the DTI tractography of each functionally distinct corticospinal tract fibre bundle was separately computed (Raffa et al., 2018, 2019). The functionally different fibre bundles taken together represent the entire corticospinal tract and reflect its functional organization (Figure 3).

2.2 | Anatomical brain mapping during surgery

2.2.1 | Superimposition of the photograph of the living brain on the surface reconstruction based on the MRI

A photograph of the exposed brain was used to identify the sulci and gyri in the operative region by matching the MRI surface reconstruction of the brain with the actual operative view by the surgeon. The photograph (2240 × 1589 pixels, dpi 72) in Portable Network Graphic (PNG) format was taken and transferred to a dedicated planning station with the brain surface reconstruction

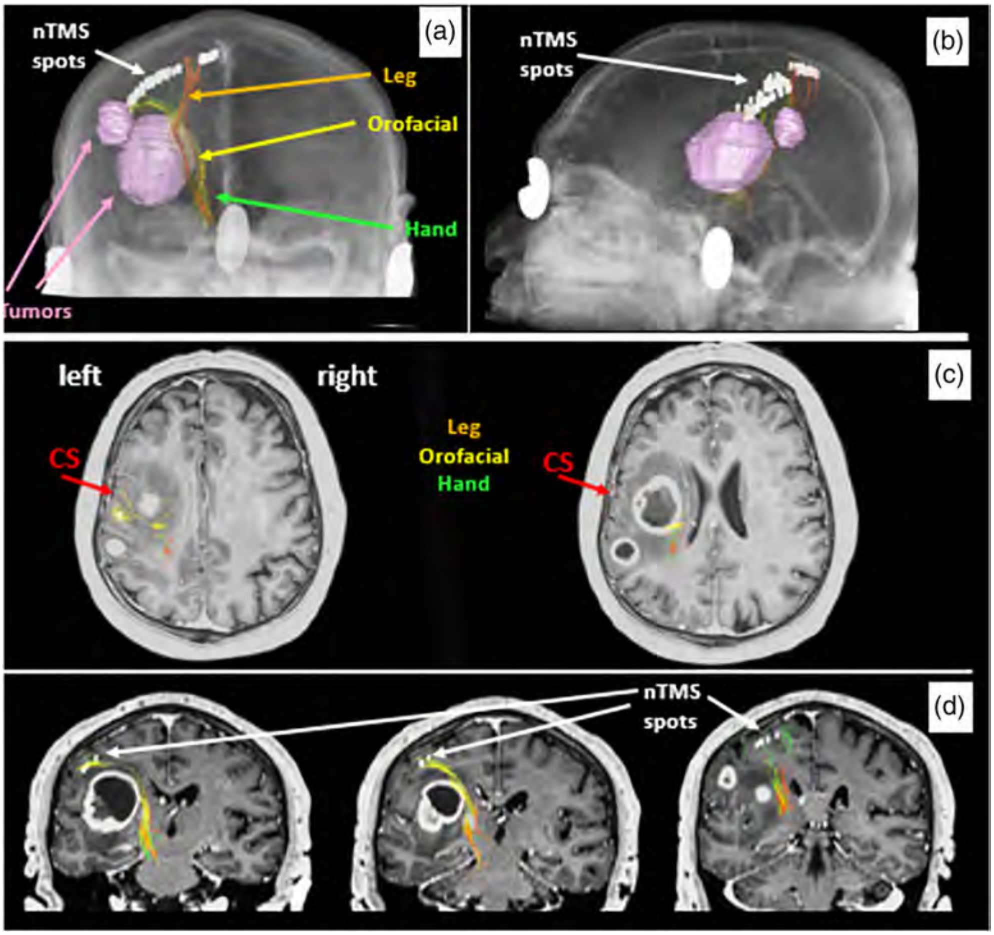

FIGURE 3 Panels A and B show the surgical planning based on nTMS DTI, that is, the three-dimensional reconstruction of the somatotopic nTMS DTI of the corticospinal tract (brown = leg fibres, green = hand fibres, yellow = corticobulbar orofacial fibres), and indicate the spatial relationship with the two tumour foci (brown). Note that the corticospinal tract passes posterior to the central sulcus, indicating that the brain tumour shifted in the posterior direction these fibres that normally run anterior to the central sulcus

containing the mapping of the relevant sulci and gyri and the axial, coronal and sagittal MRI planes previously prepared. The brain photograph was resized to match the surface reconstruction of the living brain oriented to the view on the operating table. The preoperatively prepared map of the sulcal pattern in the surgical field was then superimposed on the photograph of the living brain, and sterilized strips were positioned directly on the brain according to the sulci selected by the neurosurgeon (see Figure 4).

2.2.2 | Electrophysiological monitoring to confirm the motor cortical region in relation to the morphology of the central sulcus

The electrophysiological monitoring modalities were somatosensory-evoked potentials (SSEPs), free-running electromyography (fr-EMG), sensorimotor localization using the phase reversal technique (PRT) and DES with a subdural strip or probe. The following muscle groups were targeted with standard intraoperative needle electrodes: cranial (orbicularis oculis, masseter and orbicularis oris), upper (brachial biceps, abductor brevis of the thumb) and lower (vastus lateralis, tibialis anterior).

2.2.3 | PRT

Median nerve SSEPs were performed bilaterally as a pilot to the PRT. The contralateral median nerve was stimulated at the wrist using repetitive pulses at 3.17 Hz, 0.3-ms pulse duration applied with the smallest intensity (mA) that resulted in a clear thumb twitch. Averaged SSEPs were recorded directly from the cortical surface, using a four-contact subdural strip (reference on contralateral mastoid), placed perpendicular to and across the previously prepared maps of the sulci and gyri indicating the direction of the central sulcus.

2.2.4 | Mapping of motor function

During direct electrical stimulation with the multi-pulse technique, the stimulation intensity was increased stepwise by 1 mA until an EMG response was observed; the whole of the exposed cortical area is systematically mapped every 5 mm^2 (according to the probe spacing). A detailed drawing of the cerebral sulci and gyri relating them to the evoked phenomena constitutes the indispensable neurophysiological data to confirm on the basis of the neuroanatomical landmarks that the precentral gyrus is where motor activity was evoked.

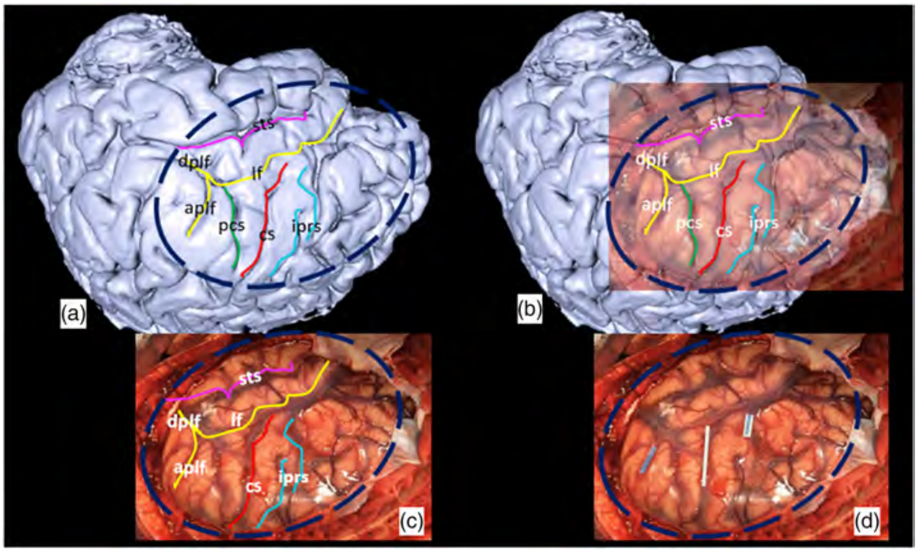

FIGURE 4 Surgical mapping. (a) Mapping of the relevant sulci and gyri on the brain surface reconstruction with the key sulci around the surgical region. The cortical surface of the brain has been oriented according to the position of the patient's head. (b) The photograph of the living brain collected soon after dural opening has been superimposed on the brain surface reconstruction of the patient brain. (c) The sulcal pattern on the photograph of the patient brain. (d) The selected sulci by the neurosurgeon according to the prepared map of the relevant sulci and gyri. The white strip indicates the central sulcus; the grey strip posterior to central sulcus indicates the ascending posterior ramus of the lateral fissure, that is, the posterior limit of the lesion. The grey/white strip anterior to the central sulcus indicates the inferior precentral sulcus, that is, the anterior limit of the lesions. Note that, on the surface of the living brain, it is not possible to localize the tumour that extends from the inferior precentral sulcus as far as the ascending posterior ramus of the lateral fissure (see Figure 2, upper panel)

3 | RESULTS

3.1 | Brain surface reconstruction

A better identification of the lesion in the depth of the brain in relation to the cortical surface can be made by using the three axes view and, importantly, their corresponding position in the brain surface reconstruction (see Figure 1a). In this patient, two foci of lesions were located in the region of the central sulcus underneath the inferior precentral gyrus, the inferior post-central gyrus and the anterior part of the supramarginal gyrus, that is, caudal to the inferior post-central sulcus and rostral to the ascending posterior ramus of the lateral fissure. Importantly, it can be seen that posterior to the central sulcus in between the two lesion foci, there was a spared white matter that relates to the corticospinal tract (see DTI results; Figure 3). In this patient, because of the tumour, the corticospinal tract was not anterior to the central sulcus but posterior to it. Thus, during surgery, particular attention was applied when operating posterior to the central sulcus (Figure 1).

3.1.1 | Mapping of the relevant sulci and gyri

The brain surface reconstruction accompanied by the axial, coronal and sagittal planes allowed a better identification of the gyri and sulci in the ROI, and these were labelled using the Atlas of the Morphology of the Human Cerebral Cortex on the Average MNI Brain (Petrides, 2019). The identified sulci and gyri are presented in Figure 1b. The foci of the lesions were not visible from the surface of the brain, and, therefore, the constant identification of the sulci allowed for localization and monitoring of the tumour position (Figure 2, upper panel). The lesions extended from the inferior precentral sulcus as far as the ascending posterior ramus of the lateral fissure. A gap in the white matter was present posterior to the central sulcus.

3.1.2 | MEPs via nTMS to confirm the motor cortical region in relation to the morphology of the central sulcus

We were able to obtain MEPs from at least one muscle of each body segment (ORB, FDI, TA). The nTMS-positive spots representing the induced MEPs from the contralateral orofacial, hand and leg muscles were depicted over the precentral motor cortex on the brain surface rendering of the patient's MRI scan to establish the motor map of the precentral motor region of the patient (Raffa et al., 2018, 2019; Rizzo et al., 2014). The precentral motor cortical area merged over the reference anatomical MRI scan of the patient was used to verify the anatomical landmarks detected through the brain morphology (Figure 2, lower panel). In addition to the confirmation of the morphological anatomical landmarks of the motor cortex, the MEPs provided motor cortex landmarks that were used as seeds together with the cerebral peduncles for the DTI computation of the corticospinal tract (see Figure 3).

3.1.3 | Image fusion and DTI somatotopic tractography of the corticospinal tract

The corticospinal tract fibres of the investigated patient were established by using the ROI corresponding to the anterolateral portion of the ipsilateral cerebral peduncle and the ROI obtained by the motor nTMS-based map of the anatomical landmark tested with MEP. The anatomo-functional mapping of the corticospinal motor pathways was used, both pre- and intraoperatively, for pre-surgical planning and as a guide for brain lesion resection (Figure 3). These images clearly showed that the corticospinal tract coursed posterior to the central sulcus, indicating that the brain tumour resulted in a shift in the posterior direction of these fibres that normally run anterior to the central sulcus. This knowledge alerted the neurosurgeon to the critical importance of that white matter region positioned posterior to the central sulcus and in-between the two lesion foci (Figure 3).

3.1.4 | Superimposition of the photograph of the living brain on the brain surface reconstruction based on the MRI

Anatomical mapping of sulci can be performed during surgery. The relevant sulci and gyri in the surgical ROI mapped on the brain surface reconstruction were superimposed on the living brain. Different coloured strips were placed on the living brain so that the margins of the brain lesions could be constantly related to the cortical surface during the surgery. This visualization was not dependent on the navigator, but rather on the sulci and gyri of the cortex that are independent of the brain tissue removed during surgery. Although the sulci shift during surgical removal, the lesion remained under the identified gyrus. Particular attention was paid during the operation when the surgeon was removing the lesion in the posterior part of the central sulcus. The latter was constantly visible on the brain surface of the patient through the strip positioned directly on it according to the mapping obtained with the superimposition of the photograph of the living brain to the brain surface reconstruction. DES for the identification of the precentral gyrus and the monitoring of the motor pathway was applied continually during surgery. A particular alert was raised when the surgical action was close to the central sulcus and posterior to it as recognized by the constant presence of central sulcus (white strip) directly positioned on the living patient brain (Figure 4d).

3.1.5 | Electrophysiological confirmation of the motor cortical region in relation to the morphology of the central sulcus

DES evoked responses showed the motor activity on the precentral gyrus that was identified on the basis of the neuroanatomical landmarks. PRT confirmed the position of the precentral gyrus. During DES, the stimulation intensity was increased stepwise by 1 mA until an EMG response was observed; the whole of the exposed cortical area was systematically mapped every 5 mm^2. Moreover, DES was used to monitor motor pathway function during tumour excision.

3.1.6 | Surgical resection and patient's outcome

The surgical resection of the tumour accounted for 96% of the preoperative tumour volume (21.12 cm^3 out of 22 cm^3). The surgery was terminated before achieving the gross total resection because of a sudden loss of MEPs. Probably such a loss was due to the surgical interference with the corticospinal tract at the latest stages of resection, which resulted in a transient post-operative facio-brachio-crural hemiparesis (3/5 at the British Medical Research Council Scale for muscle strength). Nevertheless, the patient promptly recovered from this transient motor deficit after 3 days from surgery.

4 | DISCUSSION

In the present case report, we used the simultaneous visualization of the brain surface reconstruction and the three MRI planes (axial, coronal and sagittal) for the localization of a tumour not visible from the surface of the brain. We used the intrinsic landmarks represented by the sulci and gyri to recognize the central sulcus and the sulci defining the borders of the lesions on the brain surface. The MEPs obtained by preoperative nTMS confirmed the site of the motor cortex predicted by the brain morphology of the central sulcus. The obtained cortical motor map was also used to select the motor cortex seeds together with the cerebral peduncle for the corticospinal tract computation using DTI tractography. These data showed that the corticospinal tract had been shifted because of the brain tumour and was coursing posterior to the central sulcus in between the two lesions. During surgery, as soon as the brain surface was exposed, a photograph of the operative region was obtained and transferred to a dedicated planning station to match the surface reconstruction of the patient's brain, which was mapped preoperatively. The photograph of the exposed brain was used to identify the sulci and gyri in the operative region by matching the MRI surface reconstruction of the brain with the actual operative view of the surgeon. The map of the sulcal pattern of the reconstructed brain surface was then copied on the superimposed photograph of the living brain allowing the neurosurgeon to select the sulcal landmarks for the navigation. In this case, the central sulcus, the anterior border of the tumour that was in the precentral sulcus and the posterior border of the tumour that was in the ascending posterior ramus of the lateral fissure were selected. Thus, the brain parenchymal shifting during lesion removal could be better controlled because the sulci and gyri remain independent of brain shifts and relaxation mismatch occurring in the neuronavigation system. The neurosurgeon now can monitor from the cortical surface based on the sulcal landmarks where the border of the tumour and the corticospinal tract lie and use this information together with DES intraoperative neurophysiological mapping to proceed with tumour excision safely.

The present image guidance method was provided for a real-time intraoperative tumour location. The surface reconstruction of the brain of the patient based on the three-plane view of the preoperative MRI has permitted an accurate matching with the sulci under direct vision in the exposed brain during surgery. This method can support navigation after the craniotomy is made when brain shift and relaxation mismatch with the neuronavigation system occur. In contrast to the normal brain, the corticospinal tract reconstruction through DTI in this patient was shifted posterior to the central sulcus, thus alerting the neurosurgeon when operating close and posterior to the central sulcus. The mapped superficial limits of the lesions and the constant monitoring by DES has facilitated the approach and the surgical resection by the neurosurgeon.

It is well known that there is a relationship between sensorimotor representations of different body parts and specific segments of the central, precentral and postcentral sulci in the human brain (e.g. Amiez et al., 2008;

Germann et al., 2020; Zlatkina et al., 2016). These landmarks can be provided by pre-surgically acquired morphological MRI, and, on this basis, the neurosurgeon can predict the locus of a specific body part in the pericentral region. These anatomical landmarks are then confirmed pre-surgically by using nTMS evoking specific motor responses and, during surgery, by using DES for intraoperative neurophysiological mapping and monitoring. After identification of the central sulcus, the pattern of the adjacent sulci can be recognized using appropriate brain atlases (see Petrides, 2012, 2019; Talairach & Tournoux, 1988). These atlases also provide an estimation of the location of cytoarchitectonic areas onto the three-dimensional brain sections and some of the most important cortico-cortical and cortico-fugal connections. The Petrides atlases (2012, 2019) provide the most detailed map of the sulci and gyri of the human brain in the standard stereotaxic space, that is, the MNI average standard brain, and provide a tool for MRI brain navigation in relation to particular sulci and gyri. These atlases are routinely used by neuroscientists to examine the locus of functional activity in relation to an individual's own brain structural MRI and can be used to plan the neurosurgical navigation for the removal of a brain lesion.

The sulci are topological cerebral landmarks in individual subjects and do shift with the brain parenchyma during lesion removal but remain independent from brain shift and relaxation mismatch occurring in relation to the neuronavigation system. Note also that sensorimotor activity can be obtained in an anaesthetized patient. Once the sulcal pattern is determined, the sulci become valuable landmarks for navigation in the ROI of the brain, thus reducing the inaccuracy of the neuronavigation system, especially at the later stages of surgical resection. In the present study, the sulcal pattern has been used to identify the borders of a tumour that had two main foci. It was particularly important because the corticospinal tract was coursing between the two foci of the brain tumour. Indeed, during the lesion removal, DES intraoperative neurophysiological mapping and monitoring provided critical information for the neurosurgeon who was operating very close to the corticospinal tract and had a full view of the relevant cortical surface sulcal landmarks, as well as the DTI reconstruction of the corticospinal tract.

The present report demonstrated the usefulness of mapping the perilesional sulcal patterns for brain navigation during surgery. Recent studies have also shown that functional activations can often be linked to specific morphological features of the sulci and gyri in the human brain, when the functional data are examined in individual subjects, providing better understanding of structure-to-function relationships (e.g. Amiez et al., 2006, 2008; Eichert et al., 2021; Germann et al., 2020; Yousry et al., 1997; Zlatkina et al., 2016). This additional knowledge can offer useful information to assist the neurosurgeon in decision-making regarding brain tissue resection. A demonstration of the usefulness of the function-to-structure method has been provided when the relationship between the saccadic eye movement focus and the premotor hand selection focus were examined on a subject by subject basis, that is, by paying particular attention to the sulcal and gyral pattern in individual subjects (Amiez et al., 2008, 2006; Zlatkina et al., 2016). The individual anatomical sulcal analysis was critical when considering the use of brain activation by fMRI in patients with brain tumour that would undergo neurosurgery (Amiez et al., 2008). These investigations clearly indicate that sulci and gyri represent intrinsic pointers for the localization of specific cortical cerebral regions in relation to functional predictions during intra-surgical cortical brain stimulation. Thus, sulci can be accurate landmarks for specific sites relating to specific brain functions. The neurosurgeon can use this knowledge to reduce possible functional deficit after surgery and increase knowledge of anatomo-functional correlations in the human brain (Tomaiuolo & Giordano, 2016). Finally, the sulci and gyri can be used during awake surgery to localize and stimulate specific cortical areas based on knowledge of the relation of these areas to specific cortical functions in order to avoid behavioural functional deficits after surgery.

The present case report demonstrated the usefulness of the sulcal and gyral patterns in this particular patient to carry out a 96% of brain tumour removal from the motor region without producing chronic motor deficits. Future studies could measure the brain shifting during the operation by carrying out an intraoperative MRI to compare with the preoperative MRI and thus document the extent of brain shift in relation to the present surgical approach to support further its accuracy and reliability during brain surgery.

ACKNOWLEDGEMENTS

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CONFLICT OF INTEREST

None.

AUTHOR CONTRIBUTIONS

F.T., G.R. and A.G., patient identification; A.G., F.T., G.R., A.M. and V.R., patient testing; F.T., G.R. and V.R., data processing and analysis; F.T., G.R., A.G. and M.P., data interpretation; F.T., A.G., G.R. and M.P., anatomical analysis; F.T., G.R., V.R. and M.P., manuscript writing.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1111/ejn.15668.

DATA AVAILABILITY STATEMENT

The datasets generated during and/or analysed during the current study are not publicly available due to patients' privacy, but are available from the corresponding author on reasonable request.

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