Preoperative correlation of intraoperative cortical mapping with magnetic resonance imaging landmarks to predict localization of the Broca area

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Object. Broca identified the posterior third of the inferior frontal gyrus as a locus essential for the production of fluent speech. The authors have conducted this retrospective analysis in an attempt to find readily identifiable landmarks on magnetic resonance (MR) imaging that correspond to intraoperative cortical stimulation-induced speech arrest. These landmarks demonstrate novel structural–functional relationships that can be used preoperatively to predict the location of the Broca area.

Methods. Using a neuronavigation system, sites where stimulation produced speech arrest (Broca area) were recorded in a consecutive series of patients undergoing awake tumor resections in the perisylvian territory of the dominant hemisphere. The authors reviewed 33 consecutive patients by projecting the MR imaging data sets and marking the site where the Broca area was identified. Sulcus topography was analyzed with respect to this site by scrolling into neighboring planes and classifying the frontal operculum into one of the four schemes of sulcus variability described by Ebeling, et al. The following categories of frontal operculum were found: 18 (69%) of 26 were Type I, eight (31%) of 26 were Type III, and seven cases eluded classification because of sulcal effacement. For patients with Type I anatomy, the Broca area was adjacent to, and distributed evenly around, the inferior precentral sulcus (IPS). Quantitatively, the site of speech arrest was located a mean of 2.4 ± 0.25 cm from the anteroinferior aspect of the pars opercularis, where it abuts the subarachnoid space surrounding the apex of the pars triangularis. For all patients with Type III anatomy, the Broca area was adjacent to the accessory sulcus that lies immediately posterior to the IPS. In these patients the mean distance from the anterior inferior pars opercularis was 2.3 ± 0.29 cm. The mean distance from the Broca area to the edge of the tumor for the 26 patients with clear sulcal anatomy was 1.29 ± 0.12 cm.

Conclusions. The results indicate a correlation between the structure of the frontal operculum as seen on MR imaging and the functional localization of speech arrest in the dominant hemisphere. Additionally, sulcal landmarks that can be used preoperatively to predict the location of the Broca area within the inferior frontal gyrus are described based on the patient population. This information will allow the surgeon to determine if an awake craniotomy is necessary to identify the Broca area when planning a surgical procedure near the dominant frontal operculum.

KEY WORDS • neuronavigation • landmark • cortical mapping • Broca area • magnetic resonance imaging

WHEN performing surgery near the perisylvian cortex in the dominant hemisphere, the localization of language is one of the most important factors in planning a cortical trajectory or resection and, consequently, minimizing the risk of a postoperative language deficit. Selecting patients for awake craniotomy has historically been based on the neuroimaging–confirmed localization of a lesion relative to functional cortex. Based on composite maps of neuroimaging studies obtained in large numbers of patients who have undergone language localization, functional cortex is broadly defined as the region abutting the dominant perisylvian sulcus. With the advent of intraoperative navigation systems, detailed images of gyral and sulcal morphological features are available to the neurosurgeon for correlation with intraoperative physiological findings. To date, no study has been published in which the intraoperative localization of speech arrest (Broca area) has been directly correlated with the preoperative MR images to determine if any landmarks exist that can reliably predict where the Broca area is located.

For most neurosurgeons, an important adjunct during the resection of lesions near the Broca area is awake intraoperative stimulation mapping to localize essential language areas. Currently, a change evoked in a standard repetitive measure of language function by cortical surface electrical stimulation is used for this purpose. This approach requires mapping in an awake patient and can be accomplished either extraoperatively, that is, after implantation of chronic electrodes, or intraoperatively in an exposed brain. Al-

Abbreviations used in this paper: AASR = anterior ascending sylvian ramus; ECS = electrocortical stimulation; fMR = functional magnetic resonance; IFS = inferior frontal sulcus; IPS = inferior precentral sulcus; 3D = three-dimensional.
though the mechanisms of stimulation effects on language are poorly understood, depolarization blockade or activation of inhibitory systems are the predominant effects of stimulation at those sites when an activity is altered.\(^2\)

There are no reliable surface landmarks that can be seen during surgery to identify the cortical site responsible for speech arrest. Whereas the face motor cortex can be mapped successfully with direct stimulation in an unconscious patient, there is no method to predict where the Broca area is located in relation to the inferior portion of the Rolandic cortex.

In the dominant frontal operculum, few structural guides exist for the localization of functional compared with non-functional subterritories. Neurological and neurosurgical textbooks variously describe the location of the Broca area as being in the pars triangularis of the inferior frontal gyrus, in the pars opercularis, or more commonly in the "posterior inferior frontal gyrus."\(^{12}\) Brodmann Area 44, a cortical region that is larger in the left hemisphere than in the right (an asymmetry that has been correlated with language dominance), delineates part of the Broca area within the inferior frontal gyrus of the human brain and is a critical region for speech production.\(^4\) Ebeling and others\(^{6,7,10,16,17}\) have used sagittal MR imaging correlated with autopsy studies to describe general patterns of sulcal morphological features in the frontal operculum. Using neuroimaging-confirmed and anatomical topographic characteristics of the lateral suprasylvian region, Ebeling, et al.,\(^7\) grouped frontal opercula into four different general patterns of sulcus formation (Types I–IV; Fig. 1). Thus, it would be quite helpful to use these commonly found sulcal patterns and landmarks, and to match them with stimulation sites resulting in speech arrest.

Drawing on a consecutive series of patients who underwent surgery accompanied by both intraoperative language mapping and frameless stereotactic navigation, we sought to establish principles correlating functional localization of language with sulcus topography as revealed by 3D MR imaging sets, and to relate these to the structural permutations of the frontal operculum.\(^6,10,16,17\) The purpose of this study was not only to generate parameters that a neurosurgeon may use to identify patients who would be ideal candidates for awake mapping, but also to facilitate the prediction of the Broca area in patients in whom an awake craniotomy might not be possible.

### Clinical Material and Methods

#### Patient Population

Between June 1997 and February 2002, 172 patients with left-sided and seven patients with right-sided glial tumors were admitted to the University of California at San Francisco Medical Center for awake intraoperative language mapping (in English) and tumor resection by the senior author (M.S.B.). We included all patients whose lesions were near the precentral gyrus, central sulcus, postcentral gyrus, frontal operculum, and angular gyrus, and who experienced intraoperative stimulation-induced speech arrest. In these 172 patients, we found intraoperative stimulation-induced speech arrest in 33 individuals; these patients had lesions adjacent to Rolandic cortex.

There were 18 men and 15 women ranging in age from 28 to 58 years, with a mean age of 40 years. Thirty patients were right-handed and three were left-handed; however, only two of the three left-handed patients were found to have dominant right hemispheres (in the other 31 patients the left hemisphere was dominant).

Of 172 patients, we identified 17 who were bilingual and who underwent intraoperative speech mapping. Of these 17 bilingual patients, we found speech arrest in four (all four had left-dominant hemispheres). Speech arrest was tested only in English in these patients, which is standard procedure in our unit for all patients. Because we were testing motor speech (unlike naming and reading, which is tested in all languages but is not the subject of this study), we did not expect (and have confirmed in numerous earlier cases) any difference in speech arrest (counting) based on location.
Localization of the Broca area with MR imaging regardless of the language tested. This review was conducted in compliance with a protocol approved by the Committee on Human Research (H9640-20109-01).

**Patient Characteristics**

In each patient an intraaxial lesion consistent with a glioma was diagnosed, and, overall, these lesions had a median volume of 57.3 cm³ (range 1.5–315.1 cm³). Although tumor locations and pathological findings varied widely, lesions were most often found in the insula (30.3%), and were mostly astrocytomas and oligodendrogliomas (24% each) according to pathological studies (Table 1).

**Neuroimaging Modalities**

All patients underwent preoperative MR imaging, which was used in conjunction with the intraoperative neuronavigation system (Stealth System; Sofamor Danek, Memphis, TN). Preoperative MR images were acquired on a 1.5-tesla MR unit (General Electric Medical Systems, Milwaukee, WI) at our institution. Before acquisition, 10 MR- and computerized tomography-compatible fiducial markers were placed on the patient’s scalp and forehead for use during the imaging-guided surgical procedure. Our MR imaging guidance protocol included a sagittal T₁-weighted image, an axial 3D volume T₂-weighted fast–spin echo image (TR 3000 msec, TE 102 msec), and a postcontrast (Gd-diethylene triamine pentaaetic acid) 3D spoiled gradient echo T₁-weighted sequence (TR 34 msec, minimum echo time) with 1.5-mm partitions. Axial diffusion-weighted and coronal fluid-attenuated inversion-recovery images were obtained when indicated, but were not essential to the study. Tumor dimensions were defined visually both by signal abnormalities on T₁-weighted with Gd contrast and T₂-weighted images. Postoperative images were acquired within 48 hours of surgery. The data were transferred to the operating room computer (Stealth System), where multiplanar reformatted images were produced from the T₁- and T₂-weighted 3D datasets.

**Techniques for Intraoperative Localization of the Broca Motor Speech Area**

The details of cortical stimulation are described elsewhere. In essence, standard cortical mapping was performed by stimulation of the brain surface with the Ojemann Cortical Stimulator, starting at a low stimulus (2 mA) and working up to a maximum of 6 mA by using a constant current generator producing biphasic square wave pulses (60 Hz, 1 msec/phase) to minimize the possibility of inducing a seizure.

Speech arrest was based on blocking number counting without simultaneous motor responses in the mouth or pharynx, that is, the Broca area. The site was marked with a sterile number and its location was saved on the navigational MR images before resection was initiated. This was done to minimize the effect of cortical shift, which was less than 2 mm in all cases reviewed for this study. In our experience, at this stage of the operation mannitol was not used before marking the site.

In the remaining 139 cases, in which the Broca area was not found, the surgical exposure typically excluded the region of the anterior inferior Rolandic cortex, that is, the mid- to posterotemporal lobe and the mid- to inferior parietal lobe. In cases in which the inferior Rolandic cortex is exposed and no speech arrest is found (< 1–2% of all cases in the senior author’s experience), a stimulation site that evokes motor activity has always been identified (that is, face or hand), yet the same stimulating current (and 1 mA higher) has not resulted in speech arrest; thus we are confident that our method for localizing the Broca area is quite robust.

**Topography of the IPS on MR Imaging**

The steps we took to identify the topography of the IPS were as follows: every patient who had a tumor adjacent to the frontal operculum in the dominant hemisphere underwent an MR examination not only to understand the anatomy of the tumor in reference to other contiguous structures in the brain, but also to understand the relationship of the tumor to the precentral sulcus. Once the MR imaging study was obtained, the sagittal views were of particular importance to understand the topography of the different sulci around the IPS (Fig. 1A). Type I anatomy was characterized by the juxtaposition of the AASR to the IPS and the presence of a junction between the IFS and the IPS (Fig. 1B). Type II anatomy was similar to Type I, but required the absence of a connection between the IFS and the IPS (Fig. 1C). Type III was characterized by the presence of an additional, less pronounced sulcus between the AASR and the IPS (Fig. 1D). This additional sulcus likely represents a strongly developed “sulcus diagonalis operculi.” Type IV anatomy was similar to Type I, except that it was characterized by the absence of the AASR (Fig. 1E).

**Technique to Determine the Spatial Relationship of the Tumor Margin to the Broca Area**

As indicated earlier, each patient underwent an MR examination to determine the spatial relationship of the tumor margin to the Broca area. The sagittal, coronal, and axial T₁-weighted MR images around the Broca area were reviewed and the distance from the closest tumor edge to this area was quantified in millimeters from the three different planes (see Data Analysis for details of the Broca area projection and relationship to the tumor). The shortest distance in either plane was taken as the primary measurement. To mea-
sure tumor volume, we used the 3D Unix-based software Cranial 4 Application running on the Stealth Station. The model was produced by locating each slice that contained tumor and using the drawing tool to outline the lesion. The computer takes the area outlined and the fact that the axial slices are 1.5 mm apart to calculate the volume in cubic centimeters.

Data Analysis

Capture of the images with cross hairs positioned to localize the point of speech arrest was reviewed and postoperatively by consensus with a neuroradiologist and the operating surgeon. Retrospectively, the MR image data sets used for intraoperative navigation were projected onto a screen alongside the intraoperatively generated MR image snapshot of the Broca area. The snapshot’s anatomical plane was then reconstructed onto the 3D MR image data set, as was the site of speech arrest. This permitted scrolling within the sagittal, axial, or coronal planes while a cursor marked the projection of the Broca area onto the scrolled plane. Scrolling in the sagittal plane was most useful for defining the morphological features of the sulci and gyri relative to the Broca area. In accordance with the classification scheme described by Ebeling, et al., sulcus topography was assigned to one of the four subtypes. Sulcus topography was analyzed with respect to speech arrest site(s) by scrolling into neighboring imaging planes. The mean distances were recorded from the speech arrest site(s) to the opercular tip, sylvian fissure, and central sulcus (Fig. 2). Additionally, by extrapolating speech arrest to the surface of the brain, the distance from this point to the sylvian fissure was also measured. The mean distances were also recorded from the speech arrest site to the edge of the tumor in the sagittal, axial, and coronal planes.

Two different techniques reported in Ebeling, et al., were applied for identification of the sulci. Briefly, the medial central sulcus was identified at the superior margin of the hemisphere as the next sulcus anterior to the ascending marginal ramus of the cingulate sulcus. The sulcus situated anteriorly to the lateral end of the central sulcus was identified as the precentral sulcus. Additionally, once the AASR was visualized, the next sulcus running perpendicular to and above this ramus was identified as the IFS. The topography of the lateral suprasylvian region was drawn for each patient, identifying the approximate location of the speech arrest site in relation to this area (see Fig. 3 for examples of Types I and III MR imaging). This approximation was independently confirmed by two neurosurgeons and a neuroradiologist.

Statistical Analysis

Statistical analysis was performed using SPSS software
Results

Variability Among Patients: Recognition of Type I and III Topography

Recognition of the IPS, the AASR, and other key sulcal topography was possible in 26 patients, but not in the other seven, in whom the tumor had effaced all sulcal topography of interest on neuroimages (Fig. 4). Therefore, measurements obtained in these seven cases could not be included in our calculations. Of the 26 patients (all with left-dominant hemispheres) with intact suprasylvian sulci, 18 (69.2%) demonstrated Type I frontal sulci and eight patients (30.8%) had Type III frontal sulci. No patient in this series was noted to have a Type II or IV frontal sulcus.

Type I and III Measurements

After each case analysis, and in conjunction with independent assessments by two neurosurgeons, the site of speech arrest was placed on a representative map of the patient’s frontal operculum. These maps were then merged to generate, for each frontal sulcus type, composite images of the respective speech arrest sites (Fig. 5).

In each case, four parameters were measured with respect to the frontal operculum subtype (Table 2). Overall, the mean distances from the speech arrest site to the opercular tip and sylvian fissure were 2.33 cm (range 1.07–5.6 cm) and 1.69 cm (range 0.34–4.71 cm), respectively. Among patients with Type I anatomy, these measurements were 2.28 cm (range 1.27–5.6 cm) and 1.74 cm (range 0.34–4.71 cm). In patients with Type III anatomy, the distance measured 2.40 cm (range 1.07–3.65 cm) and 1.72 cm (range 0.9–3.52 cm), respectively. For all patients, the mean distance from the speech arrest site to the central sulcus was 1.44 cm (range 0.65–2.3 cm). Among patients with Types I and III anatomy this parameter was 1.37 cm (range 0.65–1.73 cm) and 1.6 cm (range 1.05–2.3 cm), respectively (Fig. 6).

Broca Area Within the Topographic Landmarks of the IPS

Once the anatomical subtype was determined, a sagittal MR image that optimally demonstrated key sulcal landmarks (the opercular tip, the sylvian fissure, and the central sulcus) was selected (see Fig. 3 for examples of Types I and III on MR imaging). To localize most speech arrest sites for a given opercular subtype, a standardized schematic may be used. From the opercular tip, a line is drawn at 45° between the sylvian fissure and the AASR. From the sylvian fissure, at the level of the precentral sulcus, another line is drawn at 90°. From the inferior tip of the central sulcus, another line is drawn anteriorly (Fig. 6). By connecting the beginning and endpoints of these three lines, an approximate area

| TABLE 2 |
|-----------------|-----------------|-----------------|-----------------|
| Anatomy Type    | Mean Distance (cm) |
| To Opercular Tip| To Sylvian Fissure | From Surface to Sylvian Fissure | To Central Sulcus |
| overall         | 2.33 ± 0.98      | 1.69 ± 0.96     | 1.41 ± 0.99     | 1.44 ± 0.48      |
| Type I          | 2.28 ± 1.05      | 1.74 ± 1.08     | 1.49 ± 1.13     | 1.37 ± 0.45      |
| Type III        | 2.40 ± 0.84      | 1.72 ± 0.92     | 1.39 ± 1.01     | 1.60 ± 0.52      |

* Values are expressed as the mean ± the standard error of the mean.
within these points is generated for each subtype. In our study, the majority of speech arrest sites landed within this region. Among patients with Type I anatomy, 16 (89%) of 18 speech arrest sites conformed to these boundaries. For patients with Type III features, seven (87%) of eight demonstrated similar consistency. Some patients may have mass lesions that prevent even these simple calculations to provide reliable localization of the Broca area (Fig. 4); thus an awake craniotomy will be needed to verify reliably where the Broca area is located.

Proximity of the Tumor Margin to the Broca area

The proximity of the tumor edge to the Broca area was evaluated in 26 patients in whom the anatomy was clearly defined and the sulcal landmarks identified. The mean distance from the Broca area to the closest tumor margin was 1.29 ± 0.12 cm for the patients with clear sulcal anatomy (26 patients) and 0.43 ± 0.21 cm for the patients with effaced sulcal anatomy (seven patients) (p < 0.05). There was no correlation between the size of the tumor and the distance between its margin and the Broca area. Comparison of tumor volume between the patients with discernable and those with unclear sulcal anatomy showed that the mean tumor volumes were 69 ± 12 cm³ (26 patients) and 202 ± 38 cm³ (eight patients), respectively (p < 0.05). Tumor location (see Table 1) played a role in the sulcal effacement in these seven patients. These tumors were overlying the Broca area, and in four of these seven patients, the Broca area was found overlying the radiographically confirmed site of the tumor (see Fig. 4).

Discussion

When surgery is performed near the frontal operculum in the dominant hemisphere, awake language mapping is essential to verify the site(s) essential for speech arrest without motor movement, that is, the Broca area. At times, this is not possible because of patient noncompliance or the degree of mass effect. In other circumstances this may not be necessary, because a far anterior approach, that is, through the orbitofrontal cortex, is used to resect an intraxial lesion that extends behind the sphenoid wing. Thus, it would be useful to predict reliably on preoperative imaging where essential cortex for speech arrest is located, in the same way in which localization of the central sulcus, and thus, motor cortex may be determined on MR images.1

Recently the use of fMR imaging has increased in prevalence. For some patients, fMR imaging of word generation has not only been used for language lateralization,2 but also for localization of the Broca area.3 Consequently, it has been suggested that this modality may allow for language localization and presurgical planning.3 Brannen and colleagues3 conducted a study to measure the reliability, precision, and accuracy of word-generation tasks to identify the Broca area with the aid of fMR imaging. Seven patients underwent ECS mapping of speech function during an awake craniectomy, and the sites with speech function were compared with the activated locations found during fMR imaging of word generation. In all seven patients, speech areas located with ECS colocalized with areas of the brain activated by a word-generation task.3 Despite its considerable promise, however, fMR imaging remains insufficient when compared with cortical stimulation. Whereas cortical stimulation precisely localizes cortical areas for motor speech, that is, the Broca area, fMR imaging highlights many additional areas.5 Functional MR imaging has been shown to activate other regions related not only to motor speech, but also more complex language-comprehension processes. Conversely, Carpenter and colleagues5 suggest that one of the main limitations of ECS is its inability to stimulate functional areas of the brain appropriately; high-intensity stimulation can inhibit or excite neighboring regions, whereas low-intensity stimulation may be insufficient to affect target areas. Nonetheless, these authors note that cortical stimulation is a more specific modality than fMR imaging and can more precisely define critical speech areas.

Rutten and colleagues13 evaluated the use of fMR imaging as an alternative to intraoperative ECS mapping for the localization of critical language areas in the temporoparietal region in 13 patients with temporal lobe epilepsy. Before epilepsy surgery that included intraoperative ECS, the patients performed fMR imaging–monitored language tasks that included verb generation, picture naming, verbal fluency, and sentence comprehension. These authors showed
Localization of the Broca area with MR imaging

that the correspondence between fMR imaging and ECS mapping depended heavily on the statistical threshold and varied between patients and tasks. This group concluded that fMR imaging reliably predicted the absence of critical language areas within the region exposed during surgery, but that the presence of activity at noncritical language sites on fMR images limited the modality’s predictive value for the presence of critical language areas to 51%. They concluded that fMR imaging can not presently replace ECS mapping, but that it can potentially be used to speed up ECS mapping procedures and to guide the extent of the craniotomy.13 Given the current lack of precision for fMR imaging in the localization of language areas and the fact that not all centers have access to functional imaging so that word generation can be matched with these images, we concur with these authors that this modality is not yet ready to replace intraoperative ECS speech mapping.

The standard for determining preoperative language dominance is the intracarotid amobarbital test (Wada test),19 a procedure associated with patient discomfort, cost, and morbidity that “greatly exceed those of noninvasive imaging.”18 Magnetoencephalography combined with MR images forms magnetic source images, a modality used to estimate hemispherical language dominance, in lieu of amobarbital testing, and to reduce the extent of intraoperative ECS-based mapping. Szymanski and colleagues18 studied 15 patients who underwent surgery for tumors during which intraoperative language mapping was performed, and two additional patients in whom intracarotid amobarbital testing confirmed right hemisphere language dominance. Of 14 right-handed patients, 10 displayed an asymmetrical laterality index to the left. For both patients with right hemisphere dominance the laterality index was rightward. Stimulation-mapped essential language sites were found in seven of 15 patients; for six of the seven, the magnetic source image–derived laterality index was leftward. From this study it was concluded that, although asymmetry in single-equivalent dipole modeling of the late neuromagnetic field evoked by simple speech sounds correlates with hemispherical language dominance, this technique needs further development before it may be reliably used to preoperatively predict language dominance in every patient.

Currently, there are no preoperative MR imaging landmarks that accurately predict the location of a functional language site. As a consequence, the decision whether to perform an awake craniotomy remains largely based on clinical experience. By correlating awake mapping and MR imaging findings, we have attempted to address this issue by identifying the Broca area delineated by sulcal landmarks commonly found on MR imaging.

**Topography and Identification of the IPS on MR Imaging**

Ebeling and colleagues7 identified four subtypes of the frontal operculum and reported Types II and III to be of equal prevalence (5%) among 40 hemispheres studied using MR imaging, and 11 and 10%, respectively, in their anatomical studies. Notwithstanding, in our series all patients evaluated had either Type I or III morphological features.

Interestingly, within each frontal sulcus subtype, the distribution of speech arrest was unexpectedly narrow. Sites of speech arrest were generally distributed around one of two sulci, depending on the frontal operculum classification.

For instance, most patients with Type I frontal operculum had speech arrest sites distributed around the IPS, whereas patients with Type III operculum had speech arrest sites concentrated around the accessory and inferior precentral sulci. Although exceptions were noted, the majority of patients in each group demonstrated these stereotypical patterns of speech arrest location. Among patients with Type I anatomy, all but two speech arrest sites were found abutting the precentral sulcus, midway between the IFS and the Sylvian fissure. For patients with Type III operculum, in all but one speech arrest was located in a region between the precentral sulcus and the descending additional branch of the IFS. Moreover, patients with Type I anatomy were frequently noted to have speech arrest sites located midway between the IFS and the Sylvian fissure. Although the sites of speech arrest were more broadly distributed among patients with Type III than Type I opercula, these areas remained within a relatively narrow cortical field.

The software that we used in the Stealth navigation system does not account for the curvilinear dimensions of the brain, and this may be considered an imaging limitation. Nevertheless, the slices are 1.5 mm thick and the area investigated, that is, the posterior inferior frontal lobe adjacent to the Sylvian fissure, is small. Thus we can assume that any inaccuracy is very slight.

**Mass Effect of Tumor on the Broca Area and on Sulcal Topography**

Among patients with Type I anatomy, in one the Broca was located along the same rostrocaudal plane as the other speech arrest sites, but was anteriorly displaced to the level of the AASR. Notably, just beneath the frontal operculum, this patient had a large insular glioma with a volume of 64 cm³. The second atypical Type I speech arrest site was located well above the precentral sulcus and posteriorly displaced. In this case, the patient had a 62-cm³ glioma anterior to the site of speech arrest. Although it cannot be confirmed retrospectively, the mass effect from these large, strategically located lesions may account for both deviations of speech arrest sites.

For patients with Type III anatomy, speech arrest was typically located in a region between the precentral sulcus and the descending additional branch of the IFS. As observed in patients with Type I operculum, speech arrest was often midway between the IFS and the Sylvian fissure. The sole exception to this distribution pattern was in a patient in whom a glioma with a volume of 91 cm³ was situated anterior to the location where speech arrest was typically found among other patients with Type III anatomy.

In seven patients, the tumor mass had effaced sulcal topography of interest (Fig. 4); two of these patients had right-dominant hemispheres. Tumor size and location yielded neuroimaging-confined sulcal landmarks that were unidentifiable. These tumors were strategically located around the frontal operculum, the opercular tip, the Sylvian fissure, and the central sulcus. Our statistical analysis showed that in these patients with effaced sulcal anatomy the tumor volumes were significantly different from those in patients with a discernable sulcal anatomy. There was a significant difference between these two groups (in the group with effaced anatomy there was a very short distance between the tumor and the site for the Broca area). In four of these sev-
en patients, the Broca area was within the boundaries of the tumor. Although some tumors may obliterate the sulcal anatomy near the site of the Broca area, this is not always a problem. In this study we sought to address the group with clear landmarks and to locate the Broca area preoperatively within a certain cortical area to predict the risk involved in resection of tumors neighboring this critical region. It has been previously demonstrated that regardless of the degree of tumor infiltration, swelling, apparent necrosis, and gross distortion by the mass, the functional cortex and subcortical white matter may be located within tumors or in the adjacent infiltrated brain. Therefore, even with large infiltrating tumors, the Broca area may be intact, pointing out the need to perform awake mapping to maximize safe tumor resection in these functional areas. In essence, the measurement data presented in this study demonstrate that even when a tumor is within 1 to 2 cm of the Broca area, these anatomical landmarks are still valid for accurate localization of this area.

Conclusions

Despite advances in functional imaging, our ability to rely on this technique to identify the Broca area preoperatively is still evolving. Therefore, awake surgery with stimulation-induced speech arrest remains critical for identification of this region of interest. Knowing beforehand where the Broca area is likely to be found will enable the surgeon to decide if an awake operation is needed. This information would also be useful for patients who cannot tolerate an awake procedure. To date, there have been no studies in which intraoperative language mapping sites have been correlated with MR imaging landmarks. This study represents a first attempt to identify a predictable pattern of speech arrest localization given stereotyped frontal operculum anatomy viewed by MR imaging. Despite considerable variations in tumor size, location, and pathological findings, the distribution of speech arrest within each frontal sulcus subtype was highly concentrated in a small area of the frontal operculum. Drawing relatively simple lines from the opercular tip, the sylvian fissure, and from the inferior tip of the central sulcus, we outlined a region that was highly likely to contain speech arrest foci. In our study, 89 and 87% of speech arrest sites among patients with Type I and Type III anatomy, respectively, conformed to these boundaries. Most patients with Type I frontal opercula had speech arrest sites distributed around the IPS, whereas sites associated with Type III opercula were principally distributed around the accessory sulcus between the additional branch and the IPS. The measurements recorded in this study highlight key MR imaging landmarks that may serve as functional guidelines during the preoperative planning of tumor resection.

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