Electrical stimulation–induced speech-related negative motor responses in the lateral frontal cortex

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OBJECTIVE Speech arrest is a common but crucial negative motor response (NMR) recorded during intraoperative brain mapping. However, recent studies have reported nonspeech-specific NMR sites in the ventral precentral gyrus (vPrCG), where stimulation halts both speech and ongoing hand movement. The aim of this study was to investigate the spatial relationship between speech-specific NMR sites and nonspeech-specific NMR sites in the lateral frontal cortex.

METHODS In this prospective cohort study, an intraoperative mapping strategy was designed to identify positive motor response (PMR) sites and NMR sites in 33 consecutive patients undergoing awake craniotomy for the treatment of left-sided gliomas. Patients were asked to count, flex their hands, and simultaneously perform these two tasks to map NMRs. Each site was plotted onto a standard atlas and further analyzed. The speech and hand motor arrest sites in the supplementary motor area of 2 patients were resected. The 1- and 3-month postoperative language and motor functions of all patients were assessed.

RESULTS A total of 91 PMR sites and 72 NMR sites were identified. NMR and PMR sites were anteroinferiorly and posteroinferiorly distributed in the precentral gyrus, respectively. Three distinct NMR sites were identified: 24 pure speech arrest (speech-specific NMR) sites (33.33%), 7 pure hand motor arrest sites (9.72%), and 41 speech and hand motor arrest (nonspeech-specific NMR) sites (56.94%). Nonspeech-specific NMR sites and speech-specific NMR sites were dorsally distributed in the vPrCG. For language function, 1 of 2 patients in the NMA resection group had language dysfunction at the 1-month follow-up but had recovered by the 3-month follow-up. All patients in the NMA resection group had fine motor dysfunction at the 1- and 3-month follow-ups.

CONCLUSIONS The study results demonstrated a functional segmentation of speech-related NMRs in the lateral frontal cortex and that most of the stimulation-induced speech arrest sites are not specific to speech. A better understanding of the spatial distribution of speech-related NMR sites will be helpful in surgical planning and intraoperative mapping and provide in-depth insight into the motor control of speech production.

Clinical trial registration no.: NCT03641391 (clinicaltrials.gov)
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KEYWORDS direct electrical stimulation; gliomas; negative motor response; speech arrest; ventral precentral gyrus; surgical technique

Abbreviations: DES = direct electrical stimulation; HMA = hand motor arrest; KDE = kernel density estimation; NMA = negative motor area; NMR = negative motor response; PMR = positive motor area; PMR = positive motor response; SHMA = speech and hand motor arrest; SMA = supplementary motor area; vPrCG = ventral precentral gyrus.


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occurs without losing muscle tone or consciousness. The cortical area where stimulation elicits an NMR is called the “negative motor area” (NMA). Speech arrest is a typical NMR, which is defined as the arrest of ongoing speech or counting without articulatory movements. Several studies have reported the probabilistic maps of speech arrest sites based on DES.1,4,12–16 However, recent studies8,9 have found that stimulating some speech arrest sites in the posterior inferior frontal lobe also inhibited ongoing hand movements, indicating that speech arrest includes not only a speech-specific NMR (stimulation-induced speech arrest without hand motor arrest [HMA]) but also a nonspeech-specific NMR (stimulation-induced speech arrest and HMA). However, the distribution patterns of these NMR sites are still elusive.

In this study, we designed an intraoperative mapping strategy to identify different types of PMR and NMR sites and then explored the spatial relationship between them. Furthermore, we also focused on the spatial distribution of speech-specific NMR and nonspeech-specific NMR sites. Lastly, we compared the preliminary language and fine movement outcomes between NMA resection and preservation groups.

Methods
Inclusion and Exclusion Criteria for Subjects
This prospective study included cases from a consecutive series of patients who underwent awake craniotomies (n = 36) for the treatment of gliomas at Huashan Hospital between September 2018 and January 2020. All subjects were evaluated by a neurosurgeon (Y.Z.) and a senior neuropsychologist (Yan Zhou) for their muscle strength, fine motor skills (in the same way as Rech et al.17), cognitive status through the Mini-Mental State Examination,14 and language function through the Aphasia Battery in Chinese.14 Inclusion criteria were 1) newly diagnosed left-sided glioma; 2) exposure of the lateral frontal cortex (precentral gyrus or posterior part of superior/middle inferior frontal gyrus) according to presurgical plans; 3) normal cognitive status, muscle strength (grade 5), fine motor ability,17 and language function (aphasia quotient > 93.814,18) and the capacity to perform intraoperative language and motor tasks; and 4) right-handedness with left dominant hemisphere stimulation mapping. Subsequently, 3 patients were excluded for poor cooperation during the mapping procedure. This study was approved by the Institutional Review Board of Huashan Hospital. Signed informed consent was obtained from each participant prior to surgery, and each patient consented to the publication of his or her image. This study was registered with the ClinicalTrials.gov database (https://clinicaltrials.gov), and its registration number is NCT03641391.

Intraoperative Brain Mapping
The monitored anesthesia care approach was applied to balance patient pain control and arousal during awake surgery. The local anesthesia procedural details have been described in our previous studies.19,20 Upon craniotomy, the whole exposed cortical surface was stimulated with a 5-mm-wide bipolar electrode stimulator (60-Hz pulse frequency, constant bipolar square-wave current, 1-msec pulse width, 1- to 3-mA current intensity) at 1-cm intervals. The current intensity was initially set at 1 mA and was increased until a PMR was elicited when stimulating the precentral gyrus. Then, the current for NMR mapping was set at the same intensity. During the whole mapping process, a 6-contact subdural strip electrode was used to record the afterdischarge activity. A functional site was considered valid when 1) stimulation induced a PMR or an NMR, 2) the same responses were induced a minimum of 2 times out of 3 nonsequential stimulations, and 3) no afterdischarge or seizure activities were recorded. Each functional site was marked with a 0.5 × 0.5–cm² sterile tag. Photographs of the exposed cortical areas were taken to document the functional sites after completing the mapping process. The mapping procedure was recorded under the microscope, with a camera recording high-definition video of the exposed cortical surface. The Brain Mapping Interactive Stimulation System (Shenzhen Sinorad Medical Electronics Co. Ltd.)20 provides a detailed video of the patient’s face, hand, and sound. All videos were postoperatively reviewed to confirm the behavioral response corresponding to each stimulation site.

To precisely identify the PMRs and NMRs, a mapping strategy comprising four sequential tasks was applied (Fig. 1). We first asked patients to protrude their tongue, and the primary motor cortex was stimulated to identify the PMRs of the hand, lips, tongue, and jaws. Then, the patients were asked to count from 1 to 50, move the contralateral hand (alternate flexion and extension of 5 fingers at a frequency of 0.5 Hz), and finally perform the two tasks simultaneously. Sites at which stimulation induced continuous phonation of a vowel-like sound (vocalization) or made patients feel a tightening of the throat were considered as larynx motor sites. After excluding PMRs of articulators, speech arrest (speech-specific NMR) was characterized by a complete arrest of counting without HMA; HMA was defined as slowness or complete inhibition of hand movement without speech arrest and without the loss of muscle tone or consciousness; and speech and hand motor arrest (SHMA; nonspeech-specific NMR) was defined as the interruption of both counting and hand movement (Video 1).

VIDEO 1. Illustrative video of three NMRs and the intraoperative mapping strategy. Copyright Junfeng Lu. Published with permission. Click here to view.

After identifying different PMR and NMR sites, the patients were asked to perform other routine tasks, including picture naming and word reading.22 Anomia was defined as being able to say, “This is a(n) …,” but unable to name an object. Alexia was defined as being able to say, “This word is …,” but unable to read the word overtly. The entire mapping protocol was completed within 30 minutes.

Construction of 3D Surface-Based Scatter Map and Density Map
3D surface-based scatter maps and density maps were constructed following the same methodology as in our previous study.22 With the reference of intraoperative photography and neuronavigation, each functional site was
plotted onto a 3D-rendered template (ICBM 152 asymmetrical template) in MRIcron (https://www.nitrc.org/projects/mricron) according to the anatomical landmarks to obtain the Montreal Neurological Institute (MNI) coordinates (x, y, z). This part of the work was initially performed by two independent researchers (Z.Z. and Y.Z.) and then checked by Dr. Junfeng Lu (10 years of neurosurgical experience). Next, these functional sites were visualized on the template via BrainNet Viewer (https://www.nitrc.org/projects/bnv/).23

To explore the distribution pattern of different NMRs, the kernel density estimation (KDE) of a given NMR type was performed via GingerALE (version 3.0.2, http://brainmap.org/ale/). For each type of NMR, all positive sites were smoothed with a 3D Gaussian kernel with 10 mm full width at half maximum (FWHM) and further integrated into a KDE map.14,24 The MNI coordinates of the peak points and the corresponding KDE values (representing the density of these voxels) were automatically reported.25,26 Considering the limited number of HMA sites, we did not perform KDE-based analysis for HMA sites or the subsequent statistical analysis.

Postoperative Language and Motor Function Follow-Up

During the 1-month and 3-month follow-ups, each patient’s muscle strength, fine motor skills, and language function were reassessed. Since all the included patients had normal preoperative motor and language functions, we adopted a qualitative fine motor function evaluation method17 to highlight even a slight fine motor disorder. Postoperative fine motor dysfunction was defined as 1) any disorders to fine motor activities in daily life (such as driving, typing, writing, or playing musical instruments, based on the patient’s occupation and habits), or 2) disorders in finger movement or synchronized or asynchronous rotation of the hands during physical examination;17 postoperative aphasia was defined as a decrease of more than 10 points in the aphasia quotient from the preoperative baseline.20

Statistical Analysis

We performed the permutation test22 and the Mann-Whitney U-test to determine whether SHMA sites and speech arrest sites have different spatial distributions. The permutation test was used on the 3D brain surface to compare the spatial discrepancy of the two NMR types. On the z-axis, the Mann-Whitney U-test was applied to determine if they had a ventral-dorsal separation. Fisher’s exact test was performed to compare the postoperative motor and language outcomes between low- and high-grade glioma groups. A p value < 0.05 was considered statistically significant.

Results

A total of 33 patients were included. Table 1 summarizes the demographic and clinical data of the patients (detailed in Supplemental Table 1).

A total of 163 sites were identified on the lateral surface of the brain (5.62 ± 2.72 sites per patient). Among these sites were 91 PMR sites (55.83% of all sites) and 72 NMR sites (44.17% of all sites; Table 2). PMR sites were identified in 69.70% (23 of 33) of the patients. NMR sites were identified in 78.79% (26 of 33) of the patients. In particular, SHMA sites were identified in 60.61% (20 of 33) of the patients, whereas pure speech arrest sites were identified in 30.30% (10 of 33) of the patients. In addition, pure HMA was induced in 15.15% (5 of 33) of the patients, whereas no PMR or NMR sites were induced.
Spatial Distribution of PMR Sites and NMR Sites

We found that the PMR sites and the NMR sites have different cortical distributions. NMR sites were predominantly located in the anteroinferior part of the precentral gyrus, whereas PMR sites were mainly located in the posterosuperior part of the precentral gyrus (Fig. 2A). There were five different PMRs, including the movements of hand (33 [36.26%]), lips (11 [12.09%]), tongue (29 [31.87%]), jaw (7 [7.69%]), and larynx (1 [12.09%]; Table 2, Fig. 2C). The hand PMRs were located in the so-called hand knob region, while the articulator PMRs were distributed more ventrally in the precentral gyrus (Fig. 2B and C). The majority of laryngeal PMRs were located in the dorsal precentral gyrus (at the level of the middle frontal gyrus), while a few of them were present in the ventral part, which is consistent with previous studies.6,27 Other PMRs of articulators were located between them (Fig. 2C). Three different NMRs were identified: 24 pure speech arrest (speech-specific NMR) sites (33.33%), 7 pure HMA sites (9.72%), and 41 SHMA (nonspeech-specific NMR) sites (56.94%; Table 2, Fig. 2D). The majority of these three NMR sites (72.22%) were distributed in the ventral precentral gyrus (vPrCG), while a few of them were located in the pars opercularis (8.33%), dorsal precentral gyrus (8.33%), supplementary motor area (SMA; 9.72%), and postcentral gyrus (1.39%; Table 3, Fig. 2D). All languagerelated sites are summarized in Fig. 2B. Speech-related NMAs (speech arrest with or without HMA) were mainly located in the ventral premotor cortex (just anterior to articulator PMRs), as well as the pars opercularis and SMA. Anomia sites were mainly distributed in three regions: Broca’s area (pars triangularis and opercularis), posterior temporal lobe, and posterior middle frontal gyrus, which is consistent with previous studies.1,15,22,28 No alexia sites were identified in these subjects.

Spatial Differentiation Between SHMA Sites and Pure Speech Arrest Sites

For the spatial relationship between SHMA sites and speech arrest sites, we plotted the scatter map and KDE map of SHMA sites and speech arrest sites and found they were mainly located and partially overlapped in the vPrCG (Fig. 3A–C and F). The peak density for speech arrest sites was at (−66, 6, 18), while the peak density for SHMA sites was at (−64, 6, 30) (Fig. 3D and E). In addition, both SHMA and speech arrest were elicited in the pars opercularis, while only the former was induced in the SMA and dorsal precentral gyrus (Fig. 3A–C). The permutation test showed that the epicenters of SHMA sites and speech arrest sites had significantly different locations (p < 0.001; Fig. 3C). That is, the former is located in the dorsal part of the vPrCG, while the latter is located in the ventral part of the vPrCG. This ventral-dorsal distribution of speech arrest sites and SHMA sites was also confirmed by the Mann-Whitney U-test when comparing their z coordinates (p < 0.0001; Fig. 3C).

Differences in Functional Outcomes Between Resection and Preservation of the NMA

Of all 33 patients, 2 patients (6.06%) had SHMA sites removed, while the other patients (93.94%) retained all

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value (n)</th>
<th>Value (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age in yrs</td>
<td>39.0 ± 10.0</td>
<td>22–67</td>
</tr>
<tr>
<td>Female proportion</td>
<td>39.39% (13)</td>
<td>100% (33)</td>
</tr>
<tr>
<td>Tumor side: lt</td>
<td>100% (33)</td>
<td>100% (33)</td>
</tr>
<tr>
<td>Tumor location</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frontal</td>
<td>51.52% (17)</td>
<td></td>
</tr>
<tr>
<td>Insula</td>
<td>24.24% (8)</td>
<td></td>
</tr>
<tr>
<td>Temporal</td>
<td>15.15% (5)</td>
<td></td>
</tr>
<tr>
<td>Parietal</td>
<td>6.06% (2)</td>
<td></td>
</tr>
<tr>
<td>Frontotemporal</td>
<td>3.03% (1)</td>
<td></td>
</tr>
<tr>
<td>Chief complaint</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seizure</td>
<td>42.42% (14)</td>
<td></td>
</tr>
<tr>
<td>Dizziness</td>
<td>15.15% (5)</td>
<td></td>
</tr>
<tr>
<td>Limb fatigue</td>
<td>9.09% (3)</td>
<td></td>
</tr>
<tr>
<td>Olfactory halluci-</td>
<td>6.06% (2)</td>
<td></td>
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</tbody>
</table>
| n = number of patients.

DNT = dysembryoplastic neuroepithelial tumor; n = number of patients.

<table>
<thead>
<tr>
<th>TABLE 2. Characteristics of stimulation sites</th>
<th>PMR</th>
<th>NMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall response rate (n = 163)</td>
<td>55.83% (n = 91)</td>
<td>44.17% (n = 72)</td>
</tr>
<tr>
<td>Response</td>
<td>Hand</td>
<td>Articulator</td>
</tr>
<tr>
<td>Detailed response proportion</td>
<td>36.26% (n = 33)</td>
<td>63.74% (n = 58)</td>
</tr>
</tbody>
</table>

TABLE 1. Demographic and clinical features of the patient population

<table>
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<tr>
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<th>Value (n)</th>
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<td>100% (33)</td>
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<td>Limb fatigue</td>
<td>9.09% (3)</td>
</tr>
<tr>
<td>Olfactory hallucination</td>
<td>6.06% (2)</td>
</tr>
<tr>
<td>Incidental finding</td>
<td>9.09% (3)</td>
</tr>
<tr>
<td>Others</td>
<td>18.18% (6)</td>
</tr>
<tr>
<td>Histological type, WHO grade</td>
<td></td>
</tr>
<tr>
<td>DNT, I</td>
<td>3.03% (1)</td>
</tr>
<tr>
<td>Pilocytic astrocytoma, I</td>
<td>3.03% (1)</td>
</tr>
<tr>
<td>Astrocytoma, II</td>
<td>57.58% (19)</td>
</tr>
<tr>
<td>Oligodendroglioma, II</td>
<td>18.18% (6)</td>
</tr>
<tr>
<td>Glioblastoma, IV</td>
<td>18.18% (6)</td>
</tr>
</tbody>
</table>

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Differences in Functional Outcomes Between Resection and Preservation of the NMA

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NMR sites (Supplemental Tables 1 and 2). In these 2 patients, some of the SHMA points were located in the SMA and were completely wrapped in the tumor. Retaining these sites would have resulted in excessive tumor residues, which would have led to a worse prognosis in survival. In addition, previous studies have shown that resection of SMA or NMA sites in the SMA region is safe for long-term language and gross motor functions. Therefore, we sacrificed these SHMA sites and achieved gross-total resections in these 2 patients. Regarding language function, 1 (50%) of 2 patients in the NMA resection group and 10 patients (32.3%) in the NMA preservation group had language dysfunction at the 1-month follow-up. All patients in the NMA resection group had normal language function, whereas 5 patients (16.1%) in the NMA preservation group still had language dysfunction at the 3-month follow-up. Regarding fine motor function, the NMA resection group tended to have a higher fine motor dysfunction rate than the NMA preservation group at the 1-month (100% vs 22.6%) and 3-month (100% vs 9.7%) follow-ups (Supplemental Table 2). Moreover, no significant associations in the 1-month or 3-month postoperative aphasia rate and fine motor dysfunction rate were found between patients with low-grade and high-grade gliomas (Supplemental Table 3).

TABLE 3. Cortical distribution of different types of NMR sites

<table>
<thead>
<tr>
<th>Response</th>
<th>Pop</th>
<th>vPrCG</th>
<th>dPrCG</th>
<th>SMA</th>
<th>PoCG</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA</td>
<td>4</td>
<td>19</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>24</td>
</tr>
<tr>
<td>HMA</td>
<td>0</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>SHMA</td>
<td>2</td>
<td>29</td>
<td>5</td>
<td>5</td>
<td>0</td>
<td>41</td>
</tr>
<tr>
<td>Total</td>
<td>6</td>
<td>52</td>
<td>6</td>
<td>7</td>
<td>1</td>
<td>72</td>
</tr>
</tbody>
</table>

dPrCG = dorsal precentral gyrus; PoCG = postcentral gyrus; Pop = pars opercularis.
Illustrative Case

A 30-year-old right-handed female was incidentally diagnosed with an intracranial mass lesion 1 year ago before admission. The neurological examination was unremarkable. Preoperative T2-FLAIR imaging (Fig. 4A) revealed a low-grade glioma located in the posterior left middle frontal gyrus. Awake surgery using the modified mapping strategy was conducted to achieve maximum tumor resection while preserving motor and language functions. During the operation, the exposed cortical area and the patient’s face and hand were monitored and recorded (Fig. 4C–E). The areas of PMRs and NMRs were identified and protected. Tags 1–3 corresponded to tongue PMRs, tag 5 corresponded to lips PMR, and tag 12 corresponded to hand PMR. Speech arrest sites were labeled 13 and 15, while SHMA sites were labeled 16–18. Tags 6–8, 10, and 11 marked sensory response sites. Tags 19–21 corresponded to anomia sites (Fig. 4F–H). At the individual level, the distribution pattern of PMR sites and NMR sites was consistent with that of the group level. The PMR sites were located posterosuperiorly to NMR sites in the precentral gyrus. The SHMA sites were located dorsally to speech arrest sites in the vPrCG. Intraoperative MRI showed that gross-total resection was achieved, and the patient recovered without any motor or language deficits at the 1-month follow-up.

Discussion

In this study, we reported speech arrest sites to be further divided into two types: 1) speech-specific NMA (pure speech arrest sites) and 2) nonspeech-specific NMA (SHMA sites). We observed that stimulation of the nonspeech-specific NMA also inhibited hand movement, which is consistent with a previous report. The nonspeech-specific NMA was identified in 60.61% (20 of 33) of the patients and accounted for 63.08% (41 of 65) of all speech arrest sites, indicating that the majority of speech arrest we elicited during intraoperative brain mapping was not speech specific, but instead a general NMR. A potential explanation is that the NMAs may consist of hierarchical inhibitory centers of different levels, such as general inhibitory centers and effector-specific inhibitory centers. DES of the general inhibitory centers can interrupt multiple motor outputs (such as SHMA), while stimulation of the effector-specific inhibitory centers results in inhibition of specific motor function (such as pure speech arrest or pure HMA). We also found that the nonspeech-specific NMA was dorsal to the speech-specific NMA and ventral to the hand motor region. These findings suggest that the general inhibitory center is located between speech and hand motor control regions and coordinates both speech production and hand motor functions. Besides, we also found that NMR sites in the SMA could be categorized.
as general NMR sites. This suggests that the SMA, similar to the dorsal part of the vPrCG, plays a higher-level role in the inhibitory network for motor control. This also explains the SMA syndrome, which manifests as contralateral limb movement disorders and language deficit after left SMA resection. 17,32,33

Our study demonstrated 36.92% of the speech arrest sites as speech-specific sites (without motor arrest). These sites were located in the ventral part of vPrCG. One potential mechanism for speech-specific speech arrest was that DES to the corresponding sites interrupted the phonetic encoding or motor planning process of speech production. Speech production is a highly complex process involving high-level lexical-conceptual and phonological stages, phonetic encoding, as well as lower-level articulatory control. 34–37 The phonetic encoding process (sometimes also called “motor planning”) acts as a psycholinguistic-motor interface, which mediates the transformation from high-level lexical-conceptual and phonological stages to lower-level articulatory control. 36 Complete failure of this stage could lead to speech arrest. 38 According to the speech production model, the left vPrCG might serve as this psycholinguistic-motor interface processor, participating in the phonetic encoding. 39,40 Therefore, DES-induced speech-specific speech arrest in the vPrCG may result from disruption of the phonetic encoding process.

Speech-specific speech arrest could also be explained by the DES-induced activation of the physiological inhibitory pathway, which functions in the precise motor controls of articulators. Filevich et al. 41 argued that normal complex and fine movement involved an element of inhibition, and the balance between activations of the excitatory pathway and inhibitory pathway made movements neither hyperkinetic and impulsive nor hypokinetic and ineffective. Stimulation of the inhibitory pathway leads to the arrest of movements, while stimulation of the excitatory pathway leads to movement initiation. Several functional imaging studies 41–43 reported that the inferior frontal gyrus matches the areas showing increased blood oxygen level–dependent (BOLD) activity associated with response inhibition in stop-signal tasks, verifying the existence of physiological inhibitory regions. Therefore, considering that speech production requires highly coordinated movements of multiple articulators, stimulation of the inhibitory pathway for praxic control of fine movements of articulators could induce speech-specific speech arrest. Currently, whether the speech-specific speech arrest was caused by disruption of the phonetic encoding process in speech production or instead by activation of the physiological inhibitory pathway for control of articulatory movements remains unclear.

In terms of functional prognosis, although previous papers have reported that the preservation of speech arrest sites can effectively reduce the incidence of postoperative language disorders in patients, 1,44 the corresponding impact of the resection of two different speech arrest sites (SHMA and pure speech arrest) is still unknown. The preliminary results of this study suggest that resection of SHMA sites (nonspeech-specific sites) in the SMA may have no significant effect on postoperative language function, especially

![FIG. 4. Illustrative case using the modified mapping strategy. A preoperative T2-FLAIR image (A) and 1-week postoperative T2-FLAIR image (B) obtained in the patient. The patient's face (C), hand (D), and exposed cortical area (E) were real-time monitored and recorded throughout the whole mapping procedure. Positive cortical mapping sites (F) were identified and tagged. Each functional site (G) was plotted onto the reconstructed brain surface of the patient. The black dotted line shows the bone window, the red dotted line shows the central sulcus, and the blue dotted line shows the sylvian fissure. An intraoperative photograph (H) of the cortical surface after tumor removal. Panels E, F, and H are illustrations of intraoperative photos. Panels E, F, and H copyright Junfeng Lu. Published with permission. Figure is available in color online only.](image-url)
on long-term (3 months) language function. However, this study does not address the effects of the resection of language-specific sites and non-SMA SHMA sites on postoperative language function.

**Study Limitations**

In this study, given the time constraint of surgery, we did not test other effectors (such as bilateral legs and ipsilateral hand) except for the contralateral hand during the identification of NMAs. Consequently, we could not determine whether the NMR sites identified in this study were involved in the inhibition of other movements (besides those involved in speech production and contralateral movement). Future studies are required to systematically test various effectors to build a more detailed map of NMAs. In addition, the mass effect of gliomas could lead to the distortion of NMAs. However, this kind of influence may be negligible since patients in this study rarely had tumors accumulated in the precentral gyrus. Moreover, we only included patients with left-sided tumors. In fact, several studies have reported that NMRs could be elicited in both hemispheres. A more extensive database covering results from both hemispheres is urgently needed to illustrate the exact spatial distributions of different NMAs. Lastly, based on the principle of maximum function preservation, this prospective study failed to include a large sample of patients who underwent NMA resection, especially those with language-specific NMA resection, which reduced the reliability of the functional prognostic analysis.

**Conclusions**

In summary, our data demonstrate a functional segmentation of the vPrCG in terms of speech arrest. The ventral part of the vPrCG is involved in speech-specific speech arrest, while the dorsal portion of the vPrCG is associated with nonspeech-specific speech arrest. These findings not only provide insight into the motor control of speech production but also will facilitate surgical planning and intraoperative brain mapping.

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**References**


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Supplemental Information
Videos

Online-Only Content
Supplemental material is available with the online version of the article.


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