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Homotopic organization of essential language sites in right and bilateral cerebral hemispheric dominance

Clinical article

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Object. Language dominance in the right hemisphere is rare. Therefore, the organization of essential language sites in the dominant right hemisphere is unclear, especially compared with cases involving the more prevalent left dominant hemisphere.

Methods. The authors reviewed the medical records of 15 patients who underwent awake craniotomy for tumor or epilepsy surgery and speech mapping of right hemisphere perisylvian language areas at the University of California, San Francisco. All patients were determined to have either complete right-sided or bilateral language dominance by preoperative Wada testing.

Results. All patients but one were left-handed. Of more than 331 total stimulation sites, 27 total sites were identified as essential for language function (14 sites for speech arrest/anarthria; 12 for anomia; and 1 for alexia). While significant interindividual variability was observed, the general pattern of language organization was similar to classic descriptions of frontal language production and posterior temporal language integration for the left hemisphere. Speech arrest sites were clustered in the ventral precentral gyrus and pars opercularis. Anomia sites were more widely distributed, but were focused in the posterior superior and middle temporal gyri as well as the inferior parietal gyrus. One alexia site was found over the superior temporal gyrus. Face sensory and motor cortical sites were also identified along the ventral sensorimotor strip. The prevalence and specificity of essential language sites were greater in unilateral right hemisphere–dominant patients, compared with those with bilateral dominance by Wada testing.

Conclusions. The authors' results suggest that the organization of language in right hemisphere dominance mirrors that of left hemisphere dominance. Awake speech mapping is a safe and reliable surgical adjunct in these rare clinical cases and should be done in the setting of right hemisphere dominance to avoid preventable postoperative aphasia. *(DOI: 10.3171/2010.11.JNS10888)*

Key Words • **language organization** • **right hemisphere** • **Wada test** • **cortical stimulation mapping**

After early observations in aphasic patients by Broca[6] and Wernicke,[32] language function was thought to exist solely in the left hemisphere. For more than a century, the right hemisphere was believed to lack the intrinsic potential for processing language. Despite the first report by Hughlings Jackson[12] of a left-handed man with aphasia and a right hemispheric lesion in 1868, it was not until a century later with the advent of Wada testing using intracarotid amobarbital injection that essential language function was documented in the right hemisphere in a larger cohort of patients.[31] Using this technique, Rasmussen and Milner[26] showed that language is processed in the right hemisphere in 15% of non–right-handed and 4% of right-handed individuals with epilepsy. None the patients who were right-handed had bilateral language representation, whereas 15% of those who were non–right-handed did, with the other 70% showing left hemisphere representation.

Although at the time it was believed that this series of patients with epilepsy overestimated the proportion of right hemisphere speech in the general population, recent noninvasive functional imaging studies have shown that these are reliable estimates. From these studies, the prevalence of complete right hemisphere dominance in healthy left-handed individuals is estimated to be up to 22% and in right-handed individuals as high as 7.5%.[16,30] In addition, many left-handed individuals have incom-

Abbreviations used in this paper: GTR = gross-total resection; IAP = intracarotid amobarbital procedure; STR = subtotal resection; UCSF = University of California, San Francisco.

This article contains some figures that are displayed in color online but in black and white in the print edition.

plete language lateralization, demonstrating bilateral language dominance in up to 14%.[30] The degree of right hemisphere language lateralization is correlated to the degree of left-handedness, as ambidextrous individuals more commonly have bilateral language dominance.[16,20] It also appears that individuals with left, bilateral, or right hemisphere language representation do not differ significantly with respect to verbal fluency, linguistic processing, or intelligence.[17]

Given the relative infrequency of right hemisphere dominance, the anatomical and functional organization of right hemisphere language networks, when present, has not been systematically studied. In particular, it is unknown whether the right hemisphere demonstrates homologous organization (homotopic) compared with more prevalent left hemisphere dominance. A basic understanding of right dominant language processing is critical to the prevention of postoperative language deficits in those undergoing perisylvian resections. Here, using direct electrocortical stimulation for language mapping during awake speech mapping for tumor resection or temporal lobectomy for epilepsy treatment, we provide direct evidence for organization of language centers in the dominant right hemisphere. Our results demonstrate that language organization in the dominant right hemisphere shares parallel organizational features with the dominant left hemisphere, and that awake speech mapping in patients with right hemisphere dominance is effective for maximal and safe resection of tumors or seizure foci.

Methods

Patient Population

Between August 1999 and February 2010, 334 patients underwent awake intraoperative language mapping for tumor resection and epilepsy surgery at UCSF. Of these patients, only 15 (4.5%) underwent awake language mapping in the right hemisphere because of documented preoperative language dominance. Ten patients underwent tumor resection and 5 patients underwent anterior temporal lobectomy for epilepsy surgery. The committee on human research of UCSF approved this retrospective study.

Determination of Language Laterality and Preoperative Language Testing

All but one patient were left-handed or ambidextrous (for writing, drawing, and throwing), and therefore underwent language laterality evaluation by intraarterial amobarbital testing (Wada test). The one right-handed patient had significant language deficits subsequent to a right frontal lobe resection at another institution and therefore underwent Wada testing before surgery. Each Wada test result was reported as 1 of the 5 possible outcomes for hemispheric dominance: left only, left greater than right (left > right), left equal to right (left = right), right greater than left (right > left), or right only. Only patients with right-only or bilateral dominance were included in this review, and patients with left-only dominance were excluded. Preoperatively, patients underwent neurological examination with language testing performed by a neuropsychologist and/or epilepsy neurologist. Intraoperative language testing followed a standard protocol: counting numbers (from 1 to 50), and naming objects out loud in response to line drawings and reading single words out loud, both of which were displayed on an LCD monitor under computer control.

Up to 64 pictures were selected from a set of 96 pictures presented preoperatively for intraoperative testing. Concrete entities were distributed evenly across 8 semantic categories; one-half were animate and the other half were inanimate. Only pictures that were named and words that were read correctly without significant hesitation were chosen for intraoperative presentation in random order.

Awake Speech Mapping and Tumor Resection

Before surgery, most patients received midazolam (2 mg) and fentanyl (50–100 μg). During surgery, propofol (at a dose of 50–100 μg/kg body weight/min) and remifentanil (0.05–0.2 μg/kg/min) were given for sedation. After the bone flap was removed, the dura was infiltrated with lidocaine, and all anesthetics were discontinued. No anesthesia was administered during mapping.

Intraoperatively, if the frontal lobe was exposed, disruption of counting by electrical stimulation was tested. As for sensorimotor testing, any sites of consistent disruption were labeled with a sterile numbered tag. These sterile numbered tags were distributed across the entire exposed cortical area at approximately 1-cm^2 intervals. Naming and reading were tested 3–7 times at each cortical site while the patient's cortex was stimulated as described below. A neuropsychologist or neurologist was present during intraoperative language mapping. Speech arrest was defined as the complete interruption of ongoing automatic speech during the counting task without simultaneous motor responses (that is, mouth, pharyngeal, or laryngeal movement). Dysarthria was distinguished from speech arrest by the absence of involuntary muscle contraction affecting speech. Anomia was defined as the inability to name objects with fluent speech. If there was any doubt, disruption of counting was tested. Alexia was defined similarly as the inability to read single words out loud during stimulation with retained ability to speak. All cortical sites were stimulated at least 3 times. A positive site was associated with a patient's inability to speak, name objects, or read words during stimulation 66% of the time. In most cases, the location of the site was recorded with the use of navigational MR imaging.

Cortical mapping ranged from 2 to 6 mA peak-to-peak and was usually initiated at a low stimulus (2 mA peak-to-peak), which was increased to a maximum of 6 mA. A constant current generator (Ojemann Cortical Stimulator, Integra LifeSciences) delivered biphasic square-wave pulses at 60 Hz across bipolar electrodes separated by a distance of 5 mm with a maximum train length of 4 seconds, or until a response was produced. Stimulation sites were identified with sterile numbered labels and distributed per square centimeter of exposed cortex. During mapping, electrocorticographic readings were monitored for afterdischarge potentials to titrate the current to minimize the possibility of language errors due to subclinical seizure activity. When afterdischarges did not remit spontaneously in a few seconds, iced Ringer's lactate was irrigated over the involved cortex as described previously.[28]

The targeted area for resection involved the contrast-enhancing regions for high-grade gliomas and the hyperintense areas on T2-weighted MR images for low-grade gliomas, as well as areas showing mesial temporal sclerosis for epilepsy; however, when a positive language site was detected, a 1-cm margin of tissue was always preserved around this site.[11] When the field of exposure consisted of only negative sites, greater cortical exposure was not sought to identify a positive control site. The exposure for temporal lobectomy cases typically included the entire perisylvian region.

Postoperative Assessment

The extent of resection was determined by comparing MR images obtained before surgery with those obtained within 48 hours after surgery. Anything less than a GTR, defined radiographically as the absence of contrast-enhancing tissue on T1-weighted images for high-grade gliomas and the absence of hyperintense tissue on T2-weighted images for low-grade gliomas, was classified as an STR. Postoperatively, neurological examinations and language testing were conducted daily until the patient was discharged from the hospital.

Results

Patient Characteristics

Between 1999 and 2010, 15 patients underwent awake speech mapping in the dominant right hemisphere at UCSF. Their profiles are summarized in Table 1. The median age at surgery was 43 years (range 24–66 years). All patients spoke English as their primary language.

Ten patients were completely left-handed, 4 were ambidextrous, and 1 was completely right-handed (Table 1). The ambidextrous patients were left-handed for most activities, but used their right hand for some limited specific tasks (mixed dominance with left-sided predominance). The one completely right-handed patient (Case 11) had significant postoperative language impairments for 6–8 months following a right frontal resection performed under general anesthesia before referral to UCSF. Of note, his children were both left-handed, and his father was ambidextrous with his left hand predominant.

Six patients had a single presenting episode of a seizure. Six individuals had intractable seizures with durations ranging from 3 to 41 years (Table 1). One had language deficits on presentation including expressive and comprehensive aphasia. One patient presented with an incidental lesion discovered after MR imaging workup for hearing loss. Four patients had undergone previous tumor biopsy or resection at other institutions prior to presenting at UCSF. The spatial distribution and extent of cortical exposure was tailored for most tumor surgery craniotomies, while epilepsy surgeries had wide frontotemporoparietal exposure.

Results of IAP

The presurgical evaluation including MR studies and IAP testing for language dominance are summarized in Table 2. Preoperative IAP testing showed 7 patients with right-only hemispheric dominance for language. Of these, there was a possible left hemisphere contribution to speech control in at least one (Case 1), although the brief arrest following left injection may have been nonspecific, since it resolved during continued dense motor hemiparesis. Eight patients had bilateral dominance for language functions, with 1 right > left, 5 left > right, and 1 with unknown hemispheric contribution by IAP (although likely right > left). Five patients appeared to have some limited language function on the right side, with the left as the more dominant hemisphere (left > right). The specific results from the Wada injections are shown in Table 2 (although results from 1 patient [Case 9] were not fully obtainable because the Wada injections were performed at another institution where reporting did not use the same 5-category reporting method).

Distribution of Language and Motor Mapping Sites by Cortical Stimulation Mapping

More than 331 cortical sites were stimulated among all patients during awake language and motor mapping. The mean number of sites tested per patient was greater than 23 (see Figs. 2–4 and Table 3). Stimulation mapping in 7 patients resulted in 27 total "positive" sites that caused interruption of language functions upon stimulation. Twelve sites were found to produce anomia, 14 sites produced speech arrest, and 1 caused alexia. Sensory perception in the face was found at 21 sites (for example, tongue or cheek tingling), and face motor activity was found at 29 sites (for example, lip pulling or tongue deviation). We found 277 negative sites that failed to interrupt any language function or evoke sensorimotor function (see Fig. 2).

Of the 12 anomia sites, 9 were located in the posterior superior or middle temporal gyrus, 2 were located in the inferior parietal gyrus near the temporoparietal junction, and 1 was located in the middle frontal gyrus (Fig. 1, *squares*). Most of the anomia responses demonstrated either no response or a temporally delayed response immediately after the cessation of cortical stimulation. All 14 speech arrest sites were located in the ventral precentral gyrus or the posterior-most aspect of the Broca area in the pars opercularis (Fig. 1, *triangles*). The one alexia site was located in the posterior middle/superior temporal gyrus over the superior temporal sulcus (Fig. 1, *circle*). The negative sites were widely distributed in the frontal, parietal, and temporal lobes (Fig. 2, shown by "+" markers).

The patients were then divided into 2 subgroups: those with complete right hemisphere lateralization (right only) or right > left bilateral dominance for language on Wada testing (Cases 1–8), and those with left > right bilateral dominance (Cases 10–15) (Fig. 3). Anomia sites were found in 4 of 8 right-lateralized patients, but in none of the 5 left > right patients (Fig. 3A and C). One patient with bilateral language dominance but without specific knowl-

TABLE 1: Subject profile: right hemisphere language dominance*

Case No.	Age at Op (yrs), Sex	Primary Spoken Language	Handedness	Presenting Symptoms
1	59, F	English	lt	confusion, reading comprehension difficulty; language deficits after temporal biopsy in speaking & typing, partially resolved w/ significant residual dysnomia
2	49, M	English	lt	intractable seizures, onset at age 46 yrs
3	26, M	English	lt	generalized seizure—1 episode at age 26 yrs
4	59, M	English	lt	incidental finding on MRI evaluation for hearing loss
5	27, M	English	lt	intractable seizures—onset at age 20 yrs
6	29, M	English	lt	intractable complex partial seizures—onset at age 23 yrs
7	51, F	English	lt	intractable complex partial & secondarily generalized seizures—onset at age 10 yrs
8	51, F	English	ambi: lt>rt	generalized seizure—1 episode at age 51 yrs, no language deficits following biopsy 2 mos prior
9	40, F	English	lt	generalized seizure—1 episode at age 39 yrs, lt arm numbness, word-finding difficulty, 1st resection 8 mos prior, lt leg weakness, word-finding difficulty
10	24, F	English	ambi: lt>rt	seizure—1 episode at age 24 yrs
11	66, M	English	rt	seizure—1 episode at age 63 yrs, 1st resection 2.5 yrs prior w/ significant postop dysnomia for 6–8 mos, mild residual dysnomia
12	31, F	English	ambi: lt>rt	generalized seizure—1 episode at age 31 yrs, complex partial seizures w/ lt hand numbness & word-finding difficulty
13	43, F	English	lt	nocturnal seizures—onset at age 17 yrs
14	46, F	English	ambi: lt>rt	intractable simple & complex partial seizures—onset at age 32 yrs
15	39, M	English	lt	intractable complex partial & generalized seizures—onset at age 28 yrs

* ambi = ambidextrous.

edge of hemispheric contribution by Wada testing (Case 9) was found to have anomia sites and is therefore likely to have right > left bilateral dominance for language (Fig. 3B). Speech arrest sites were identified in 8 of the 13 patients tested. Of these patients, 5 had right lateralization, 2 had left > right lateralization, and 1 had unknown lateralization. Thus, at least for speech arrest, there is actually a poor correspondence between the specific functional deficits observed during hemisphere anesthetization and that elicited by direct cortical stimulation.

Motor mapping was also performed in 12 of the 15 patients and involved stimulation of sites that evoked movements and/or sensory disturbances. Motor sites involving the lips, jaw, or tongue were identified, and were all located in the precentral gyrus (Fig. 2). Sensory sites involving the lips, jaw, or tongue were identified and all were located in the ventral postcentral gyrus as expected (Fig. 1). A case example of intraoperative language mapping is provided in Fig. 4.

Functional Language Outcome

Based on postoperative imaging findings, 8 of the 10 patients with tumors had undergone GTR and 2 had undergone STR due to involvement of the tumor with positive motor and/or language sites. The histopathological findings are summarized in Table 4. Postoperatively, language function was assessed immediately after and daily for several days following surgery. Completely preserved language function was observed in 11 patients. Two patients had transient worsening of language function, which improved by the time of hospital discharge, and 1 patient had a significant global aphasia, which evolved into an expressive aphasia that lasted for months. One of the patients with transient postoperative paraphasias reported mild residual word-finding difficulties 9 months postoperatively, but was also undergoing concomitant radiation therapy and chemotherapy for a high-grade glioma. Other functional deficits included persistent left hemiparesis (in 1 patient).

Discussion

In this study, we documented the organization of essential language sites in 15 rare patients with preoperative evidence of significant language function in their right hemispheres who underwent right-sided tumor and/or cortical resections for epilepsy. Overall, we observed organization in the right hemisphere that was homologous to that described for left hemisphere language dominance.[8,10,21,22,25,27] Speech arrest sites were clustered in the ventral precentral gyrus and the pars opercularis, whereas locations of anomia sites showed greater distribution across frontal, temporal, and parietal lobe locations. Consistent with the landmark paper by Ojemann and colleagues,[21] we also observed considerable vari-

TABLE 2: Preoperative IAP and MR imaging results*

Case No.	Lang Dom†	IAP Findings (if known): Rt Injection	IAP Findings (if known): Lt Injection	MRI Findings: Size (cm)	MRI Findings: Structures Involved
1	rt only	global aphasia, impaired comprehension, & constant paraphasic errors including neologisms, >20 min	no speech or response to commands for 2 min w/ rapid return during motor paresis, no paraphasias	5	medial temporal lobe including hippocampus
2	rt only	mild dysarthria, naming deficit, & paraphasias	obtundation (not valid)	6	STG, uncus, insula, & inferior frontal lobe
3	rt only	global aphasia	normal	3	posterior inferior frontal lobe
4	rt only	speech arrest, naming & reading intact	dysarthria, mild reading deficit, right visual field cut, naming intact	3	MTG & pSTG
5	rt only	initial speech arrest, naming, comprehension, & repetition impaired for 3 min; to baseline in 10 min	initial dysarthria only, no language deficits	4	posterior, middle, & inferior temporal gyrus
6	rt only	global aphasia	normal	—	posttraumatic encephalomalacia
7	rt only	paraphasic errors, decreased comprehension	infrequent errors	—	anterior temporal lobe
8	bilat (rt>lt)	reading comprehension impaired, perseveration, speech and naming intact; possible ACoA cross-fill	not tested	3	posterior frontal lobe, rt IFG
9	bilat	NA	NA	5	posterior inferior frontal lobe
10	bilat (lt=rt)	speech arrest	speech arrest	6	posterior inferior frontal lobe
11	bilat (lt>rt)	difficulty reading words for 5 min, other functions intact	severe impairment in comprehension & naming, paraphasias in naming & repetition	4	superior & middle frontal gyrus, frontal operculum
12	bilat (lt>rt)	dysarthria for 2 sec, difficulty following complex commands	no speech for 2 min followed by rapid motor & speech recovery	6	frontal operculum
13	bilat (lt>rt)	initially anomic, comprehension, repetition, & reading impaired during recovery, naming intact; to baseline in 10 min	naming, comprehension, repetition, & reading impaired throughout period of recovery from hemiparesis; to baseline in 11 min	—	mesial temporal lobe
14	bilat (lt>rt)	3 min to 1st words, no paraphasic errors, comprehension intact	7 min to 1st words, literal paraphasia, prolonged comprehension problems	3	anterior temporal lobe
15	bilat (lt>rt)	decreased speaking, talking after 1 min then gradual recovery	decreased speaking, talking w/in 30 sec, prolonged coprolalia, 6 min before 1st appropriate words	—	mesial temporal lobe

* ACoA = anterior communicating artery; IFG = inferior frontal gyrus; Lang Dom = Language Dominance; MTG = middle temporal gyrus; NA = not available; pSTG = posterior superior temporal gyrus.
† Based on Wada testing.

ability between patients with respect to location of essential language sites. We found preliminary evidence that patients with complete right dominance or symmetrical dominance were more likely to have anomia sites than those with left dominance. Speech arrest appeared to be present in several cases irrespective of the degree of lateralization.

Interpretation of language dominance using amobarbital anesthetization is straightforward when the most common pattern is obtained, that is, global aphasia during the period of maximum drug effect on one side, and continued speaking without significant errors on the other side.[14] It is well known that bilateral speech representation encompasses a wide range of patterns, and it is difficult to classify these patterns consistently across centers.

Even patients with clear-cut right hemisphere language dominance as measured by hemisphere anesthetization may have varying degrees of bilateral representation for different language functions. This is consistent with the wide range of individual variability in stimulation mapping results among left hemisphere–dominant individuals. Lateralization of individual language functions (for example, naming or reading) is potentially independent and likely varies with the degree of language dominance.

Few studies have reported the results of electrocortical stimulation mapping of language organization in the right hemisphere. An elegant study by Duffau and colleagues[9] examined the configuration of corticosubcortical language networks in the right hemisphere of 9 left-handed patients. They also discovered a pattern of language distribution quite similar to that reported classically for

TABLE 3: Intraoperative electrocortical stimulation findings*

Case No.	Craniotomy Exposure	Total No. of Sites	Motor Map	Language Mapping† Anomia Yes/No	Anomia Site(s)	Arrest Yes/No	Arrest Site	Alexia Yes/No	Alexia Site
1	temporal	23	NT	yes	1. pMTG/pSTG	NT		yes	1. pMTG/pSTG
2	frontotemporal	29	yes	yes	1. dorsal premotor	yes	1. IFG-pars opercularis	no	
3	frontal	25	yes	no		no		no	
4	temporal	19	NT	no		NT		no	
5	frontotemporoparietal	36	yes	no		yes	1. vPCG 2. IFG	no	
6	frontotemporoparietal	>20	yes	yes	1. IPG 2. IPG	yes	1. vPCG 2. IFG	NT	
7	frontotemporoparietal	>20	yes	yes	1. aSTG	yes	1. IFG	NT	
8	frontoparietal	24	yes	no		yes	1. vPCG	no	
9	frontotemporoparietal	24	yes	yes	1. mSTG 2. pMTG 3. pMTG 4. pSTG 5. pSTG	yes	1. vPCG	no	
10	frontal	20	yes	no		no		no	
11	frontal	18	yes	no		no		no	
12	frontoparietal	33	yes	no		yes	1. vPCG 2. vPCG 3. vPCG	no	
13	frontotemporoparietal	>20	yes	no		yes	1. vPCG 2. vPCG	NT	
14	frontotemporoparietal	>20	yes	no		no		NT	
15	frontotemporoparietal	>20	yes	no		no		NT	

* aSTG = anterior STG; IPG = inferior parietal gyrus; mSTG = middle STG; NT = not tested (usually because of limited exposure); pMTG = posterior MTG; vPCG = ventral precentral gyrus.

† Numbers in these columns signify independent and discrete essential language sites.

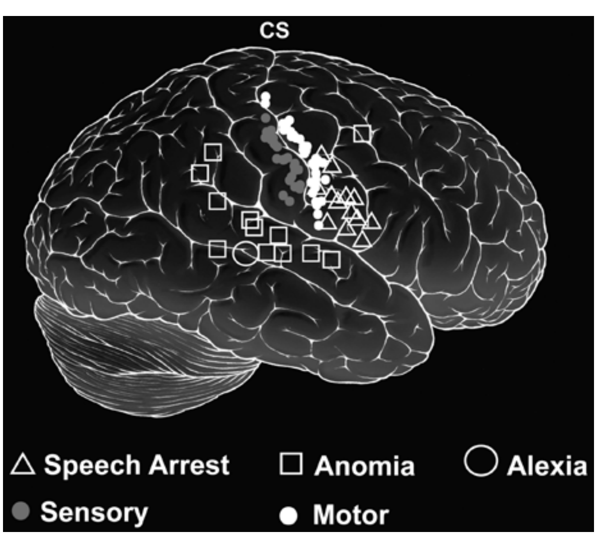

Fig. 1. Composite of all positive motor, sensory, and language sites by cortical stimulation (CS). *Triangles* represent speech arrest sites, *squares* represent anomia sites, and the *circle* represents the alexia site. Sensory sites for face, mouth, and jaw are represented by *gray dots*. Motor sites including face, hand, and arm are represented by *white dots*.

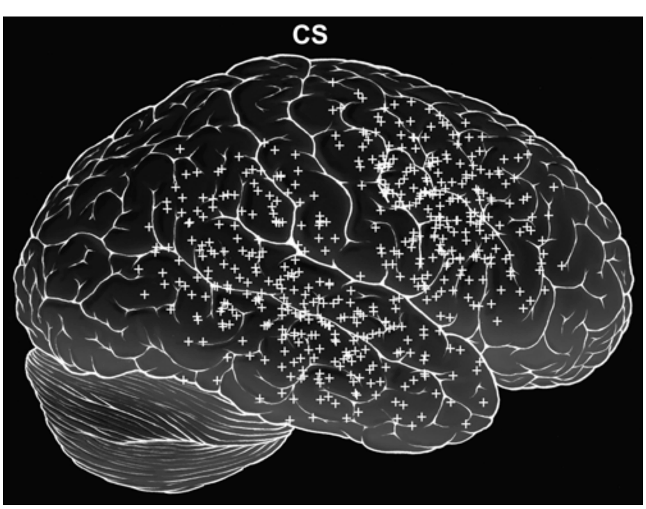

Fig. 2. Negative language and motor mapping sites (+). Composite of all sites that failed to induce a language or motor response by direct cortical stimulation.

the left hemisphere. While the authors provided a comprehensive study of the language network, Wada testing was not performed, and the degree of language lateralization was unknown in their series. Nonetheless, our conclusions drawn with Wada findings are consistent with theirs, suggesting that language processing in the dominant right hemisphere is enabled by the same overall connectivity and anatomical layout to the left hemisphere.

It is important to note that in most right-handed individuals, even though the left hemisphere is essential for language production and comprehension, the nondominant right hemisphere plays an important role in the prosody and paralinguistic aspects of normal speech. Prosody is the rhythm, pitch, and stress in speech that gives nuance to language and also conveys meaning. Patients with right perisylvian lesions lack prosodic modulation of speech and are often unable to judge emotional tone in the speech of others.[23,24] In addition, damage to the nondominant hemisphere produces impairments in the ability to coherently integrate, contextualize, and infer meaning from language.[3,19] Functional imaging studies have confirmed the involvement of the right hemisphere of right-handed individuals in processing prosodic features and detection of emotional tone, which are crucial for effective communication.[2,7]

In addition to its role in normal language processing, the compensatory recruitment of the right hemisphere has been well documented in certain pathologies in the dominant left hemisphere. Functional imaging studies have demonstrated activation of the right inferior frontal gyrus in the subacute phase of language recovery following left hemisphere stroke.[18,29] Another group found that repetitive transcranial magnetic stimulation disrupted verb generation in 4 of 9 patients 10 days after the stroke, supporting the idea that the right inferior frontal gyrus helps to support left language function during poststroke recovery.[33] Furthermore, several studies have shown by functional MR imaging, magnetoencephalography, and Wada testing that patients with long-standing left temporal lobe epilepsy have a significantly higher rate of right or bilateral language dominance than the general population.[1,4,5,13] Together, these studies support the notion that when language function in the left hemisphere is compromised, interhemispheric reorganization can take place. In contrast, our cohort includes a majority of patients with brain tumors and epilepsy with no known pathology in the left hemisphere that would have caused reorganization of language functions. Rather, they have naturally occurring right or bilateral hemisphere language dominance.

Our results also demonstrated that intraoperative language mapping in the right hemisphere in the vicinity of negative language sites provides excellent functional outcomes for right–language dominant tumor or epilepsy surgery. We were able to achieve a GTR in the majority of patients with tumors (80%). Furthermore, only 2 patients showed transient aphasia that completely resolved, and 2 patients with baseline language deficits continued to have expressive aphasia postsurgically. The increase in severity of the language deficit that occurred in a patient after temporal lobectomy was unexpected, because the patient's resection did not include cortex with mapped language function.

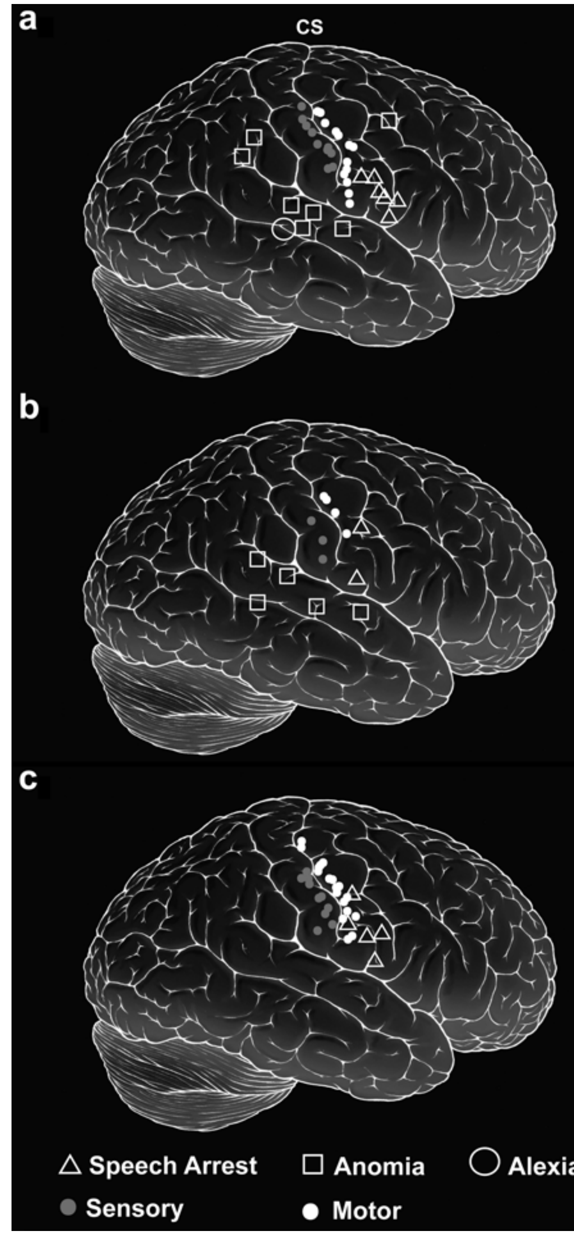

Fig. 3. Right versus bilateral hemisphere language dominance. **a:** Positive language and motor mapping sites for patients with complete right hemisphere lateralization or right > left bilateral dominance for language on Wada testing (8 patients [Cases 1–8]). **b:** Language and motor sites for a patient with bilateral language dominance of unknown hemispheric contribution shows a right dominant pattern of positive language sites. **c:** Positive language and motor sites for patients with left > right bilateral dominance (6 patients [Cases 10–15]).

This study points to the importance of careful history taking and physical examination in patients who are candidates for right-sided cortical procedures. The patient in Case 11 is an example of a patient who had some indications from history that he might have language function in his right hemisphere and had a worsening of language function following tumor resection at another institution. Furthermore, this study includes a patient with an unexpectedly poor language outcome following lobectomy de-

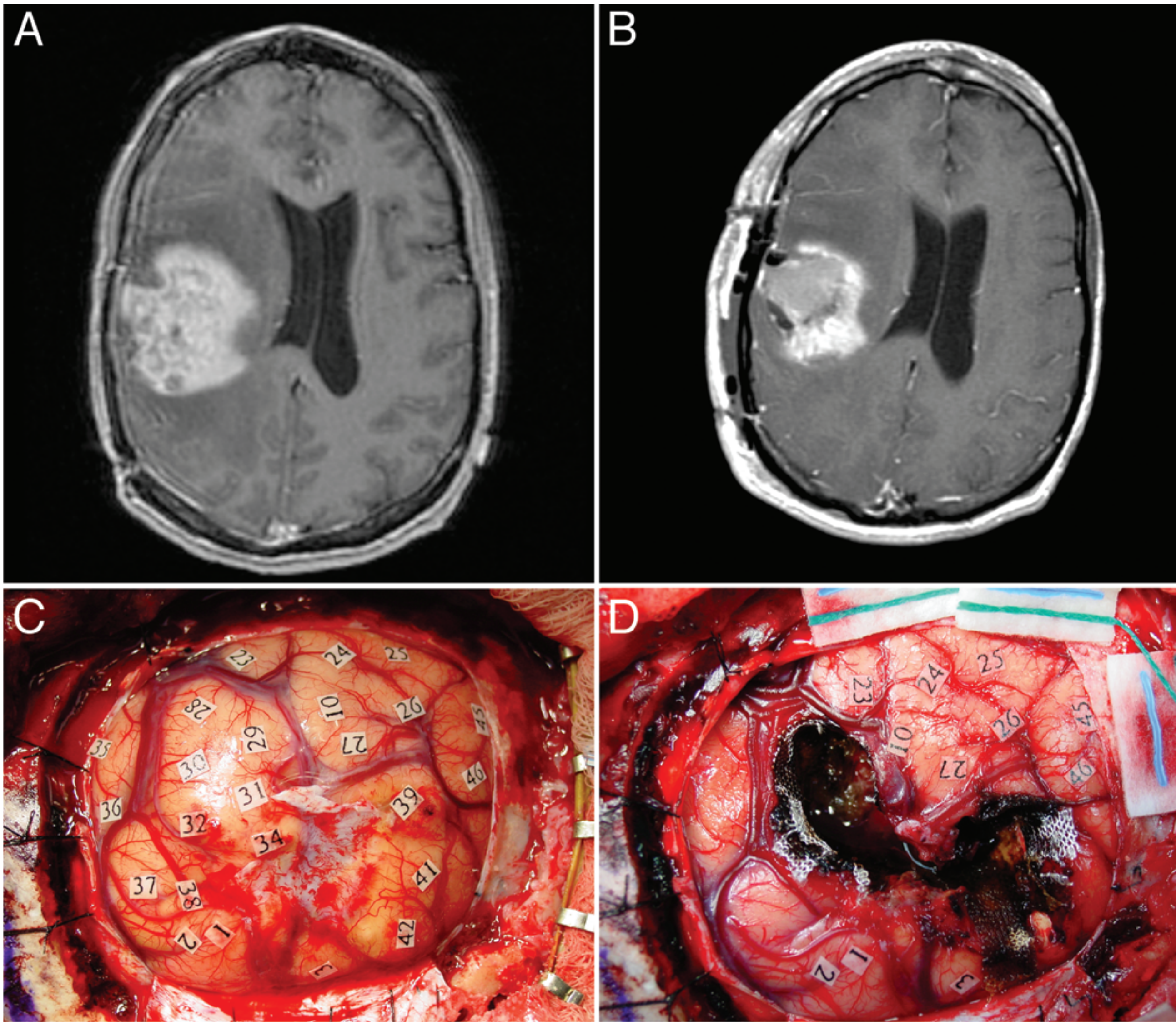

Fig. 4. Magnetic resonance and intraoperative images. **A:** Preoperative T1-weighted Gd-enhanced MR image demonstrating a 5-cm right-sided nonenhancing mass in the posterior inferior frontal lobe. **B:** Postoperative image showing STR of the lesion. **C and D:** Intraoperative photographs obtained in the same patient, demonstrating sites of direct cortical stimulation and tailored resection to spare essential language and motor areas. Areas 1 and 2 = motor face; Area 3 = motor and sensory throat and jaw; Area 10 = speech arrest; and Areas 23, 24, 27, and 45 = anomia.

spite careful language mapping. This underscores the fact that cortical speech mapping does not always preclude a significant new language deficit and that subcortical mapping of white matter tracts might have been useful here as well.[9]

This study does not provide data to correlate with ongoing work using functional MR imaging or magnetoencephalography to determine language lateralization.[15,20,30] However, the fact that patients with equal language lateralization or variations from left-only language dominance may have significant language function in their right hemispheres means that these studies must be carefully correlated with Wada test results to ensure that they are appropriately sensitive to these rare cases. Otherwise, patients may be subjected to procedures with risks that could be obviated by language mapping.

Conclusions

Altogether, our findings demonstrate new insights to the functional organization of cortical language networks in the dominant right hemisphere. Furthermore, language mapping in the dominant right hemisphere with direct electrocortical stimulation is a safe and reliable method to minimize morbidity for resection located within or near language pathways.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: Chang, Berger.

TABLE 4: Surgical outcome and pathology*

Case No.	Extent of Resection	Pathology, WHO Grade	Postop Language Deficits
1	GTR	anaplastic astrocytoma, Grade III	none
2	GTR	oligoastrocytoma, Grade II	none
3	GTR	oligodendroglioma, Grade II	none
4	GTR	anaplastic astrocytoma, Grade III	transient paraphasic errors, dysnomia, persistent mild word-finding difficulty
5	GTR	ganglioganglioma, Grade I	none
6	ATL	astrogliosis	transient global aphasia evolved to expressive aphasia
7	ATL	astrogliosis	none
8	STR, limited by eloquent cortex	oligodendroglioma, Grade II	none
9	STR, limited by eloquent cortex	GBM, Grade IV	transient mild dysnomia & severe difficulty w/ counting & concentration, further tumor progression w/ lt hemiparesis & naming intact
10	GTR	anaplastic astrocytoma, Grade III	transient dysarthria/counting, repetition, & naming intact
11	GTR	GBM, Grade IV	none
12	GTR	anaplastic astrocytoma, Grade III	none
13	ATL	cortical dysplasia	none
14	ATL	dysembryoplastic neuroepithelial tumor	none
15	ATL	astrogliosis	none

* ATL = anterior temporal lobectomy; GBM = glioblastoma multiforme.

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