Selective surgery in the language-dominant temporal lobe carries significant risks for language deficits, especially when performed in the hemisphere with greater representation of language function. In the majority of right-handed people it is assumed that the dominant hemisphere for most language functions is the left. However, the possibility that such functions depend on right-hemisphere structures is not negligible and it is even more significant among left-handed individuals. In addition to variations in lateralization, the precise location of language-specific cortex within the hemisphere that is important for language function is also highly variable. Space-occupying lesions, arteriovenous malformations, or chronic neurological conditions such as intractable epilepsy can cause distortions of the usual cortical map for language functions. Currently, mapping of language-specific cortex is performed using two invasive methods: the intracarotid amytal test (Wada test) for determination of hemispheric dominance for language and intraoperative cortical stimulation for localization of language-specific areas within the hemisphere that supports language function. Both procedures are associated with significant risks and add considerable cost and time to the treatment protocol.

The Wada test is presently used to determine hemispheric dominance for language, but it does not provide information regarding the precise location and extent of language-specific cortex. In addition, it is an invasive procedure with the potential to cause morbidity. Information obtained preoperatively regarding the precise location of language areas could be valuable for determining the surgical approach and the extent of the craniotomy and for limiting the amount of time spent intraoperatively performing mapping procedures. Recent advances in performing real-time imaging of task-induced cerebral activation have stirred many expectations regarding the ability to provide, noninvasively, maps of the extent of cortical involvement in language function. Such techniques would be particularly helpful in guiding surgical decisions if they could reveal language-specific areas with precision. Ultimately, verification of any of these techniques will depend on direct comparisons with electrical stimulation mapping and surgical results. In a previous report we described the development of a technique for mapping receptive language–specific cortex with magnetic source (MS) imaging and its successful application in four patients. In this report we present detailed information on this technique, which has been significantly refined on the basis of experience accumulated recently with a substantially larger group of patients.

### Object
In this paper the authors demonstrate the concordance between magnetic source (MS) imaging and direct cortical stimulation for mapping receptive language cortex.

### Methods
In 13 consecutive surgical patients, cortex specialized for receptive language functions was identified noninvasively by obtaining activation maps aided by MS imaging in the context of visual and auditory word-recognition tasks. Surgery was then performed for treatment of medically intractable seizure disorder (eight patients) and for resection of tumor (four), or angioma (one). Mapping of language areas with cortical stimulation was performed intraoperatively in 10 patients and extraoperatively in three. Cortical stimulation mapping verified the accuracy of the MS imaging–based localization in all cases.

### Conclusions
Information provided by MS imaging can be especially helpful in cases of atypical language representation, including bihemispheric representation, and location of language in areas other than those expected within the dominant hemisphere, such as the anterior portion of the superior temporal gyrus, the posteroinferior portion of the middle temporal gyrus, the basal temporal cortex, and the lateral temporoccipital cortex.

### Key Words
- magnetic source imaging
- magnetoencephalography
- cortical localization
- language cortex
- epilepsy surgery
- functional brain mapping

---

**Localization of language-specific cortex by using magnetic source imaging and electrical stimulation mapping**

**PANAGIOTIS G. SIMOS, PH.D., ANDREW C. PAPANICOLAOU, PH.D., JOSHUA I. BREIER, PH.D., JAMES W. WHELESS, M.D., JULES E. C. CONSTANTINOU, M.D., WILLIAM B. GORMLEY, M.D., AND WILLIAM W. MAGGIO, M.D.**

Departments of Neurosurgery, Neurology, and Pediatrics, The University of Texas–Houston Medical School, Houston, Texas

**Object.** In this paper the authors demonstrate the concordance between magnetic source (MS) imaging and direct cortical stimulation for mapping receptive language cortex.

**Methods.** In 13 consecutive surgical patients, cortex specialized for receptive language functions was identified noninvasively by obtaining activation maps aided by MS imaging in the context of visual and auditory word-recognition tasks. Surgery was then performed for treatment of medically intractable seizure disorder (eight patients) and for resection of tumor (four), or angioma (one). Mapping of language areas with cortical stimulation was performed intraoperatively in 10 patients and extraoperatively in three. Cortical stimulation mapping verified the accuracy of the MS imaging–based localization in all cases.

**Conclusions.** Information provided by MS imaging can be especially helpful in cases of atypical language representation, including bihemispheric representation, and location of language in areas other than those expected within the dominant hemisphere, such as the anterior portion of the superior temporal gyrus, the posteroinferior portion of the middle temporal gyrus, the basal temporal cortex, and the lateral temporoccipital cortex.

**Key Words** • magnetic source imaging • magnetoencephalography • cortical localization • language cortex • epilepsy surgery • functional brain mapping
Clinical Material and Methods

Patient Population

We examined 13 consecutive patients (seven females and six males) who underwent surgery for resection of tumors (four patients), cavernous angioma (one), or epileptogenic tissue (eight) at Hermann Hospital in Houston, Texas. In all cases the planned excision potentially involved language-specific cortex. Surgery was performed in the left temporal lobe in 12 patients and in the right perisylvian region in one left-handed patient. Four of these patients (Cases 2, 4, 5, and 11) have been reported briefly in our previous publication.11 All patients signed informed consents after the nature of the procedures was explained to them and prior to participating in the study. All experimental procedures were approved by the University of Texas Institutional Review Board.

Preoperative MS Imaging Testing

A detailed account of the assumptions that underlie the MS imaging procedures and of the development and standardization of the language tasks used has been provided in our previous report.11 Here we summarize the main features of the tasks and the MS imaging recording procedures. Language-specific brain activity was elicited using two word-recognition tasks: one delivered in the visual and the other in the auditory modality. The same set of words was used in both word tasks, in a different order each time. It consisted of 110 abstract English nouns with scores of 3 or lower on the Paivio Concreteness Scale.9 Two word-recognition tasks: one delivered in the visual and the other in the auditory modality. The same set of words was used in both word tasks, in a different order each time. It consisted of 110 abstract English nouns with scores of 3 or lower on the Paivio Concreteness Scale.9 Word frequency ranged from “very frequent” (scored AA) to nine occurrences per million for some words.11 The spoken words were produced by a native speaker of English with a flat intonation (duration between 300 and 750 msec, mean 450 msec), digitized with a sampling rate of 22,000 Hz and 16-bit resolution and stored on a portable computer (Macintosh: Apple Computer, Inc., Cupertino, CA). In both tasks, the stimuli were arranged in three lists of 43 words, 33 of which were repeated in every block (targets) mixed with 10 new items (distractors). An equal number of “frequent” (scored A) and very frequent (AA) words were assigned to each stimulus category on a block-by-block basis. Targets and distractors did not differ significantly in mean concreteness ratings (2.2 and 2.1, respectively).

Spoken words were delivered binaurally via two 5-m-long plastic tubes terminating in ear inserts at an 80-dB Sound Pressure Level measured at the patient’s outer ear (A scale). Visual words were shown through a projector (LCD Model XG-ES90U; Sharp Electronics Corp., Mahwah, NJ) on a white screen located approximately 1.5 m in front of the patient. The word stimuli subtended 1 to 4° of horizontal and 0.5° of vertical visual angle, respectively. Exposure duration was set at 1 second, whereas in both tasks the interstimulus interval varied randomly between 3 and 4 seconds across trials. Patients were asked to lift their right index finger whenever they detected a target (repeated) word. The patients in Cases 1, 5 through 8, 10, 11, and 13 were examined on both tasks, whereas in Cases 9 and 12 only the visual version of the word-recognition task was administered, and in Cases 2 through 4 only the auditory version was given (see following for more details).

Recordings were made in a magnetically shielded room with a whole-head neuromagnetometer (BTi: Biomagnetic Technologies, Inc., San Diego, CA) that consisted of 148 magnetometer coils placed in a cryogenic container (dewar). The signal was filtered online with a bandpass filter between 0.1 and 50 Hz, digitized for 1000 msec (250-Hz sampling rate) including a 150-msec prestimulus period, and subjected to an adaptive filtering procedure that is part of the machine’s software. These steps are necessary to minimize the amount of low-frequency magnetic noise present in the recordings. The single-trial event-related fields (ERFs) elicited by target stimuli were then averaged together after removing those during which an eye movement or blink had occurred (as indicated by a peak-to-peak amplitude in the electrooculogram channel in excess of 50 μV). A minimum of 85 ERF epochs was used to calculate each averaged waveform. Finally, the averaged epochs were digitally filtered with a lowpass 20-Hz filter.

The intracranial generators of the observed ERFs (henceforth referred to as “activity sources”) were modeled as single equivalent current dipoles (ECDs), which were fitted at successive 4-msec intervals by using the nonlinear Levenberg–Marquardt algorithm.13,16 For a given point in time, the ECD-fitting algorithm was applied to the magnetic flux measurements obtained from a group of 34 to 38 magnetometers, always including both magnetic flux extremes. The ECD computation was restricted to latency periods during which a single pair of magnetic flux extremes dominated the left and/or right half of the head surface. Although a variety of source-modeling approaches have been proposed by different investigators,3,7 we decided to use a single-ECD model that is part of the BTi software. The algorithm used in this study searched for the ECD that was most likely to have produced the observed magnetic field distribution at a given point in time. The ECD solutions were considered satisfactory after meeting two criteria: first, a correlation coefficient of at least 0.9 between the observed and the “best” predicted magnetic field distribution. Second, the 95% confidence volume index was taken into consideration in many cases (see Discussion for more details). The confidence volume corresponded to the region that was most likely to contain the source of the observed magnetic field distribution (that is, in 95% of all possible repetitions of the measurement). The procedure for precise coregistration of ECD coordinates on structural, T1-weighted, magnetic resonance (MR) images (TR 13.6 msec; TE 4.8 msec; recording matrix 256 × 256 pixels, 1 excitation, 240-mm field of view, and 1.4-mm slice thickness) is described in detail elsewhere.16

Intraoperative Stimulation Mapping

Propofol was used for intraoperative sedation. Following exposure of the cortex, electrical stimulation was applied using a four- or six-contact subdural strip consisting of platinum disk electrodes 1 cm in diameter that were embedded in a silastic sheath at 1-cm intervals. A pair of adjacent electrodes from the set of four or six were connected to the output terminals of a stimulator (model S-12; Grass Instruments, West Warwick, RI) and placed on the exposed cortical surface at locations selected in sequence.
Magnetic source imaging–based language mapping

to evaluate the entire exposed cortical surface. Stimulation was performed using 3- to 5-second-long trains of square-wave pulses (at 500 μsec/phase at 50 Hz). For each pair of contacts the current was varied from 5 to 17.5 mA until either a deficit occurred or afterdischarges were observed on the simultaneous electroencephalographic (EEG) recordings.

Various aspects of receptive and expressive language function were evaluated using three tasks: repetition of spoken sentences, comprehension of spoken sentences, and confrontation naming. The last task was performed using color drawings of simple objects presented on a portable computer screen placed at a distance of approximately 60 cm in front of the patient. Testing was performed by a clinical neuropsychologist who was blinded with respect to MS imaging results. To assess receptive language, the train of electrical pulses was presented at the beginning of the spoken sentence or at the onset of the picture, depending on the task. Expressive language was tested by initiating stimulation immediately after sentence presentation. Positive results were always verified by repeating stimulation at the same site at least twice and assessing performance in the absence of stimulation. In all patients, we were able to rule out the possibility of language deficits being the result of interference with motor pathways by ensuring that speech arrest was in no case accompanied by positive motor signs such as facial/tongue movements. Moreover, the lack of reported evoked sensations during stimulation leads us to question the possibility that sites associated with language deficits were part of the sensory cortex. Effective stimulation at each site was obtained at stimulation levels that did not produce afterdischarges, thus negating the likelihood of receptive language deficits being associated with alteration or loss of consciousness. The site of effective electrical stimulation was noted by the surgeon and documented photographically. In some patients (Cases 2–5) the frameless stereotactic system (model SMN; Zeiss, Oberkochen, Germany) was used for localization. When photographs were available, matching the two sets of images was accomplished with the aid of measurements relative to anatomical landmarks, such as the temporal tip and distinct vascular formations, that were easily distinguishable on both the MR images and the photographs. Then, the images containing the MS imaging map and the marked site(s) of successful electrical stimulation were compared.

**Extraoperative Stimulation Mapping**

Electrical stimulation mapping was performed extraoperatively in three patients (Cases 11–13) by using multicontact subdural grids placed on the lateral surface of the temporal lobe. Stimulus parameters were as follows: square-wave pulses of 500 μsec in duration per phase at 50 Hz, and train duration of 3 to 5 seconds. Stimulation intensities of up to 11.5 mA, or to the point of afterdischarge, were used. Simultaneous EEG recording was performed using the subdural grid. Receptive language function was assessed using confrontation naming, sentence repetition and comprehension, and a modified token test. In the token test the stimuli consisted of a row of five different-colored circles above a second row of five different-colored squares. The patient was asked to “Point to the red square after the blue circle,” for example, and stimulation coincided with the presentation of the command. Any form of error, or significant increase in response time, was considered an error. Stimulation and no-stimulation trials were randomly intermixed, and at least five or more errors were required to consider a site to be involved in language production. Comparison of MS imaging and stimulation mapping results was performed directly by overlaying MS imaging–derived activity sources on high-resolution MR images acquired after grid placement. In this way we were able to determine the exact location of source clusters in relation to specific electrode contacts.

**Summary of Cases**

**Case 1**

This 52-year-old left-handed man underwent a right frontotemporal craniotomy for resection of a large glioblastoma with surrounding vasogenic edema located in the posterior frontal lobe. The tumor occupied the frontal operculum and was exerting pressure on the temporal lobe. Preoperative MS imaging testing, in which the auditory and visual versions of the word-recognition task were used, suggested bilateral representation of receptive language function, as indicated by a nearly equal number of activity sources in perisylvian areas in both hemispheres. Overlapping clusters of activity sources obtained in the context of all three tasks were found in the upper posterior portion of the superior temporal gyrus just beneath the tumor mass (Fig. 1a). These clusters of activity sources were observed at approximately 290 to 320 msec after stimulus onset in both sessions. This area was also active later, at approximately 410 msec, as indicated by sources observed during the second testing session (visual task). Electrical stimulation at 13.5 mA in this area was associated with significantly prolonged response latencies for both repetition and confrontation naming. No other disruptions of receptive language were observed after extensive mapping of the entire area surrounding the tumor and also of the posterior part of the middle temporal gyrus. In addition, preoperative somatosensory testing with MS imaging revealed the location of the central sulcus posterior to the tumor. Because the location of language-specific and sensorimotor cortex was found to be close to, yet not encapsulated by the lesion, an aggressive resection was performed. A neurological examination performed in the immediate postoperative period indicated the presence of mild dysarthria but no dysphasia. The dysarthria resolved over a period of 2 weeks.

**Case 2**

This 32-year-old right-handed woman presented with headaches, earaches, and dizziness accompanied by intermittent paresthesias in her right arm. Results of the neurological examination were unremarkable, with the exception of a slight reduction in pinprick sensation in the right upper extremity. Magnetic resonance imaging revealed a 2-cm left cavernous angioma located deep in the temporoparietal region adjacent to the atrium of the lateral ventricle; the lesion had hemorrhaged on at least two occasions. The angiogram revealed no evidence of an arte-
riovenous malformation. As part of the preoperative MS imaging procedure, language-specific activity was mapped during performance of two repetitions of the visual version of our word-recognition task. In both sessions, a clear preponderance of activity sources was found in the left hemisphere, indicating left-hemisphere dominance for language. Reliable late-activity sources, found in the context of both testing sessions, were clustered posterior to the traditional Wernicke’s area near the angular gyrus (Fig. 1b). Clusters of activity sources occurred at essentially the same latency after stimulus onset in both sessions (between 220 and 240 msec). Based on this finding, a more posterior surgical approach to the lesion was made. On exploration of the entire exposed cortical area with

Fig. 1. Preoperative MR images obtained in the patients in Cases 1 to 5. Clusters of MS imaging–derived activity sources are shown in green or blue (auditory word-recognition task) and red or yellow (visual word-recognition task). For the patients in Cases 1 to 4 (a–d) who were tested only on the visual version of our task, red and yellow circles represent activity sources obtained during two separate replications of the task. The patient in Case 5 (e) was only examined on two replications of the auditory version of the word-recognition task. In the corresponding panel (e) green circles represent activity sources obtained during the first, and blue circles activity sources obtained during the second replication of the task. Perpendicular lines on MR images from the patients in Cases 2 through 5 were adapted from the stereotactic system and indicate sites of effective electrical stimulation.
Magnetic source imaging–based language mapping

electrocortical stimulation during the execution of sentence-repetition and object-naming tasks, a small region that consistently produced receptive language deficits was identified. This region was essentially coextensive with the clusters of MS imaging–derived activity sources. No significant change in linguistic abilities was noted postoperatively.

**Case 3**

This 16-year-old right-handed girl developed partial seizures following a motor vehicle accident. One year later, a T2-weighted MR image revealed a partially cystic lesion, approximately 1.5 cm in diameter, in the left posterior temporal lobe. The patient suffered from congenital mild-to-moderate hearing loss, and dyslexia had been diagnosed. She had no other neurological abnormality. Because of these limitations, language-specific activation during the preoperative MS imaging testing was elicited using a picture-naming task and an easier version of our visual word-recognition task. In view of the patient’s reading disability, cerebral dominance was assessed using the data from the naming task, which clearly indicated greater left-hemisphere representation of language function. In both sessions, late-activity sources clustered near the superoposterior margin of the lesion (Fig. 1c). These clusters represented activity occurring between 400 and 440 msec in the naming task and between 350 and 390 msec in the visual word-recognition task. Intraoperatively, the entire area surrounding the tumor was explored using electrical stimulation mapping. The only region that was associated with consistent deficits in repetition and naming was located just superior and posterior to the tumor. With the aid of the stereotactic system this area was determined to be essentially identical to the one indicated by MS imaging preoperatively. The entire lesion was resected, and no change was noted in neurological or language function in the immediate postoperative period.

**Case 4**

This 25-year-old right-handed man presented with partial seizures and significant impairment in receptive and expressive language, occurring over the last 3 years. Computed tomography and MR studies revealed a large left temporal cystic tumor. The cystic portion of the tumor was attached to the left middle cerebral artery and was causing significant midline displacement, with compression of midbrain and mesial temporal structures. The MS imaging evaluation was performed 6 days before surgery in the context of two repetitions of the visual word-recognition task. Results showed a clear preponderance of activity sources in the left hemisphere, indicating left-hemisphere dominance for language function. Two distinct clusters of activity sources were found, one in the posterior part of the superior temporal gyrus and the other in the middle portion of the inferior temporal gyrus, approximately 5 cm from the tip of the temporal lobe. The first of these clusters represented neurophysiological activity that occurred at a latency of 400 to 430 msec after the onset of the word stimuli. Corresponding latency values for the second cluster were 200 to 220 msec (Fig. 1d). Intraoperatively, electrical stimulation mapping was performed on an extensive portion of the exposed temporal lobe surface, including the inferior temporal gyrus. Two distinct regions were found to be consistently associated with deficits in repetition and comprehension. With the aid of the stereotactic system these areas were found to overlap with those predicted by MS imaging preoperatively. Stimulation of the cortex located between these regions produced no language deficits. Postoperative examination revealed complete preservation of speech and motor functions.

**Case 5**

This 68-year-old right-handed man presented with episodes of dysphasia and weakness in the right arm caused by a recurrent glioblastoma located in the left temporoparietal region. Preoperative MS imaging testing in which the auditory word-recognition task was used in two sessions revealed consistent clusters of activity sources near the anterior and medial margins of the lesion. Figure 1e displays two such clusters representing neurophysiological activity observed between 600 and 650 msec (medial cluster) and between 350 and 370 msec (lateral cluster) after stimulus onset. Intraoperatively, interference with the ability to repeat and comprehend sentences was achieved with stimulation of the cortical surface near the anterior border of the tumor in the region indicated by MS imaging (marked by the lateral cluster of activity sources). Based on this information, complete resection of the tumor was achieved. Postoperatively, the patient’s dysphasia and right-hand weakness were unchanged.

**Case 6**

This 18-year-old right-handed man had intractable cryptogenic temporal lobe epilepsy with onset at 6 months of age. Preoperative MS imaging testing in which both the visual and the auditory versions of the word-recognition task were used showed a preponderance of activity sources in left-hemisphere perisylvian regions, indicating greater left-hemisphere representation of receptive language functions. This finding coincided with the results of the Wada procedure. Two clusters of activity sources were observed and both of them localized to the superior temporal gyrus, one in the traditional Wernicke’s area at approximately 6.5 cm, and the second at 3.5 to 4.5 cm from the anterior tip of the temporal lobe. These two clusters of activity sources can be seen in Fig. 2a. Sources in the anterior cluster represented activity occurring between 300 and 310 msec (auditory task) and between 330 and 350 msec (visual task). The posterior cluster was only observed during the auditory task (560–570 msec). Intraoperative stimulation mapping showed consistent interference with repetition and sentence comprehension on electrical stimulation in both areas, that is, with electrode contacts located at 3 to 5 cm and at 6 to 7 cm from the tip of the temporal lobe along the superior temporal gyrus. The locations of effective stimulation sites are indicated by open rectangles in Fig. 2a and in subsequent figures. Stimulation in the area of the posterior cluster of MS imaging activity sources produced disruption in both repetition and confrontation naming.

**Case 7**

This 36-year-old right-handed woman had suffered
from intractable, cryptogenic complex partial seizures since infancy. Video EEG monitoring with scalp electrodes and interictal MS imaging examination indicated a left temporal lobe focus for this patient's seizures. Her MR image revealed left mesial temporal sclerosis. Preoperative MS imaging mapping of language-specific cortex was performed in the context of both the auditory and visual versions of the word-recognition task. A clear preponderance of late-activity sources was found in the left hemisphere in both testing sessions, indicating left-hemisphere dominance for language. This conclusion was later verified by the results of the Wada procedure. Areas involved in receptive language functions were defined as those that became engaged during both versions of the

P. G. Simos, et al.
Magnetic source imaging–based language mapping

task at approximately the same latency period after stimulus onset. Such a region was found to be located on the superior temporal gyrus between 4.5 and 6 cm from the tip of the temporal lobe (Fig. 2b). Some involvement of the superior aspect of the middle temporal gyrus was also indicated. Activity in this region occurred between 400 and 450 msec in the auditory task and between 480 and 500 msec in the visual word-recognition task. Intraoperative stimulation mapping was entirely consistent with MS imaging results. Significant interference with the ability to repeat and comprehend spoken sentences was attained with electrical stimulation of sites located 4 to 4.5 and 6 to 6.5 cm from the tip of the temporal lobe. This zone was located primarily on the superior temporal gyrus and extended slightly into the middle temporal gyrus.

**Case 8**

This 32-year-old right-handed man had suffered from intractable, cryptogenic temporal lobe epilepsy since childhood. Preoperative MS imaging testing in which both the visual and auditory versions of the word-recognition task were used showed a preponderance of activity sources in left-hemisphere perisylvian regions, indicating greater left-hemisphere representation of language functions. This finding coincided with the results of the Wada procedure. Clusters of activity sources observed reliably in both testing sessions were found exclusively in the superior temporal gyrus extending between 5 and 6 cm from the tip of the temporal lobe (Fig. 2c). These sources reflected activity that occurred between 300 and 320 msec (auditory task) and between 420 and 450 msec after stimulus onset (visual task). Intraoperative stimulation mapping showed consistent interference with repetition and sentence comprehension on electrical stimulation in the same area, that is, only with electrode contacts located between 5 and 6 cm from the tip of the temporal lobe along the superior temporal gyrus.

**Case 9**

This 52-year-old right-handed woman had a history of intractable complex partial seizures with onset in childhood. The epileptogenic zone was identified in the left anterior mesial temporal lobe by combined use of stereotactically implanted depth and subdural electrodes and interictal MS imaging examination. Preoperative mapping of language-specific cortex with MS imaging was performed in the context of two repetitions of the auditory word-recognition task. Because the patient was diagnosed as having dyslexia, the visual version of this task was not included in the language-mapping protocol. A clear preponderance of late-activity sources in the left hemisphere indicated that hemisphere’s dominance for language, a finding that was corroborated by the results of the Wada procedure. On closer examination, clusters of activity sources in the dominant hemisphere revealed two distinct regions that consistently became engaged in this task, one in the supramarginal gyrus and the other in the middle portion of the superior temporal gyrus, approximately 4 to 4.5 cm from the tip of the temporal lobe (Fig. 2d). The anterior cluster represented activity observed between 330 and 360 msec after stimulus onset, whereas activity reflected by the posterior cluster was observed between 390 and 430 msec after stimulus onset. Subsequent intraoperative stimulation mapping verified that both regions were indeed critically involved in receptive language functions. One of the two areas was located in the supramarginal gyrus immediately posterior to the region in which stimulation produced positive motor signs in the hand and face. Confrontation naming of simple objects was also transiently impaired (at comparable thresholds) following stimulation of either area.

**Case 10**

This 28-year-old man had a history of febrile convulsions in infancy and had experienced intractable partial complex seizures since the age of 14 years. He was found to have left-sided mesial temporal sclerosis and left-sided temporal seizure onset. His neurological history was otherwise unremarkable. Preoperative MS imaging testing in which both the visual and auditory versions of the word-recognition task were used showed a preponderance of activity sources in left-hemisphere perisylvian regions, indicating greater left-hemisphere representation of language functions. This finding was corroborated by the results of the Wada procedure. Clusters of activity sources observed reliably in both testing sessions were found predominantly in the superior temporal gyrus extending between approximately 4 cm from the tip of the temporal lobe and 6 cm back (Fig. 2e). Intraoperative stimulation mapping that covered the entire length of the superior temporal gyrus and a significant portion of the middle temporal gyrus verified that the region indicated by MS imaging was indeed associated with receptive language deficits when electrically stimulated. Interference with the ability to repeat sentences and respond to simple questions was noted after stimulation at contacts located between 3.5 and 5.5 cm from the anterior tip of the temporal lobe. A subsequent temporal lobectomy spared the entire superior temporal gyrus and involved resection of the middle and inferior temporal gyri up to 6 cm from the tip, including the amygdala and hippocampus. The patient had no speech deficits postoperatively.

**Case 11**

This 17-year-old right-handed boy had presented with complex seizures at age 13 years. We performed MS imaging mapping of language-specific cortex, in the context of both versions of the word-recognition task, before placement of subdural electrodes. A clear preponderance of late-activity sources in the left hemisphere indicated that hemisphere’s dominance for language, a finding that was corroborated by the results of the Wada procedure. The MS imaging data revealed a dense cluster of activity sources in the posterior part of the superior temporal gyrus (Fig. 3a). This cluster contained sources observed during the visual task between 580 and 600 msec and during the auditory task between 520 and 540 msec after stimulus onset. Electrical stimulation mapping was performed extraoperatively by using a large 64-contact grid covering the greatest portion of the temporal lobe surface. Superimposition of the MS imaging data on an MR image obtained while the grid was still in place showed that the...
A cluster of language-specific activity sources was located beneath Contacts 21, 13, 20, and 12, which, when stimulated, produced significant disruption of the ability to repeat sentences and comply with simple verbal commands. The position of these contacts is indicated by the rectangle in Fig. 3a.

Case 12

This 56-year-old woman had a history of intractable complex partial seizures with onset at 9 years of age. She had previously undergone a left anterior temporal lobectomy with resection of mesial structures 3 years before the present examination, but she continued to have seizures postoperatively. The MS imaging testing was performed before placement of subdural electrodes in the context of two repetitions of the auditory word-recognition task. The visual task could not be administered because the patient was unable to read the printed words comfortably without corrective lenses. Clusters of activity sources observed reliably in both sessions were located between 5.5 and 7.5 cm from the anterior tip of the temporal lobe (Fig. 3b).

The patient then underwent placement of a 32-contact grid covering the entire lateral surface of the temporal lobe. When superimposed on MR images acquired after grid placement, MS imaging clusters of activity were located beneath Contacts 13 to 15. Cortex specialized for receptive language functions, as evidenced by stimulation-induced interference with repetition and comprehension of spoken sentences, was identified under the same contacts. Postoperatively, the patient had a mild expressive dysphasia, which resolved in 3 days.

Case 13

This 33-year-old woman presented with intractable complex partial seizures with onset at 18 years of age. Before placement of subdural electrodes, which would be used for both prolonged EEG monitoring and language mapping, we performed MS imaging mapping by using both versions of the word-recognition task. Dense clusters of activity sources were observed in the context of both tasks, and showed significant spatial and temporal overlap in the posterior third of the superior temporal gyrus (Fig. 3c).
Magnetic source imaging–based language mapping

Activity sources found in this region during the auditory version of the task occurred between 300 and 330 msec after the onset of the word stimuli. Corresponding latencies of activity sources found during the visual word-recognition task were 600 and 650 msec. As shown in Fig. 3c, significant interruption of receptive language functions (sentence repetition and comprehension) was found with stimulation at Contacts 4 and 8 (enclosed by the rectangle), that essentially overlapped with the clusters of MS imaging–derived activity sources. The patient underwent a lateral and mesial temporal lobectomy. Although her postoperative course was marked by an episode of aseptic meningitis, she experienced no language deficits.

Discussion

In 13 consecutive patients, a perfect agreement was found between MS imaging–based noninvasive mapping of receptive language-specific brain areas and intraoperative language mapping in which electrocortical stimulation was used. The results attest to the validity of MS imaging–based localization of language-specific cerebral activation by demonstrating that regions that contain clusters of activity sources accounting for late ERFs are indeed those that play a crucial role in receptive language functions. The present report highlights the utility of the MS imaging mapping protocol, especially in patients with atypical language representation. We used the MS imaging technique successfully to determine bilateral language representation in a left-handed patient (Case 1) and also to identify areas involved in receptive language function located outside the traditional anatomical borders of Wernicke’s area. Such areas were found, as indicated by both MS imaging and intraoperative stimulation mapping, in the anterior portion of the superior temporal gyrus (Case 9), the posteroinferior portion of the middle temporal gyrus (Case 3), basal temporal cortex (Case 4), and the lateral temporooccipital cortex (Case 2). In all of these atypical cases, MS imaging–derived information was found to be extremely useful in surgical planning by: 1) helping to determine the optimal extent of the craniotomy; 2) helping to assess surgical risk; and 3) helping to tailor the location and extent of the cortical resection. The accuracy of the localization procedure was apparently unaffected by the type and extent of pathological conditions in the brain, or the presence of preoperative language and cognitive deficits. The tasks we developed for language mapping can be performed easily by patients with basic communication skills. The entire procedure is typically completed rapidly, involving a maximum 40-minute recording session.

These results strongly support the necessity for using late-activity sources, that is, those occurring after the resolution of the first major ERF component that typically reflects modality-specific activation in primary sensory cortices. Practically, the clinical significance of activity sources found earlier than approximately 200 msec for auditory presentation and approximately 300 msec for visual presentation is questionable.

In an effort to ensure that observed activity sources not only represent neurophysiological activity that occurs beyond the early stages of sensory processing, but also reflect the engagement of processes that are specific to language, we searched for brain regions that become active during both the auditory and the visual version of the word-recognition task. As we have previously demonstrated in neurologically normal volunteers, this activity tends to occur at approximately the same latency after onset of stimulus in both tasks.11

Although the replicability of MS imaging–derived activity sources is excellent when testing neurologically intact individuals (who are also highly motivated and cooperative), increased variability in the precise spatial and temporal features of the activation maps is to be expected in the case of neurosurgical patients. Signal quality is often less than optimal in these individuals for a number of reasons ranging from structural brain abnormalities to cognitive and attentional deficits. In view of these difficulties, and to optimize the selectivity of our mapping procedure, we compare activation maps constructed independently during two repetitions of the same language task. Typically, only those aspects of the activation map that are replicated in both sessions are used to identify the language-specific cortical regions.

Care should be taken to screen patients for the presence of a reading disability. Activation profiles in these individuals in the context of reading tasks can be dramatically different from those of normal, relatively skilled readers, rendering the results from the use of the visual word-recognition task (and any reading task for that purpose) suspect for misinterpretation. In patients with reading disabilities, we typically use two versions of the auditory word-recognition task, involving a different set of words each time to prevent habituation.

The criteria used for considering activity sources as “acceptable” representations of observed ERFs should be adapted to the recording conditions characteristic of each patient. In our previous investigations we have adhered to stringent criteria, namely a correlation coefficient of 0.90 between observed and predicted (according to physical laws) magnetic flux distributions, and a confidence volume of 3 cm3. However, our growing experience suggests that these parameters should only be used as indexes of the relative importance of computed activity sources in each patient rather than as absolute cutoff points.

In principle the single-dipole model that we have used for computing activity sources may not be optimal for constructing activation maps that are specific to complex cognitive/linguistic functions. However, our data clearly suggest that this method can be used successfully to detect the most salient and, importantly, the clinically relevant features of the map of cortical activation associated with the engagement of language-specific brain operations. Recently developed mathematical procedures hold much promise for further improving the accuracy as well as enabling better determination of the fine details of the spatiotemporal map of language-specific brain activation. This can be achieved by taking into account the irregularities of the brain surface, and by using alternative methods for modeling activity sources.3,7

Given the success in mapping temporal lobe language areas (Wernicke’s region) with MS imaging, we are now assessing the validity and reliability of various tasks that could be used for the identification of frontal lobe areas critically involved in aspects of expressive language function.
References


Manuscript received March 8, 1999.
Accepted in final form June 17, 1999.
Address reprint requests to: Panagiotis G. Simos, Ph.D., Department of Neurosurgery, The University of Texas Medical School, 6431 Fannin, Suite 7.148, Houston, Texas 77030. email: asimos@heart.med.uth.tmc.edu.