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Locating the Central Sulcus: Comparison of MR Anatomic and Magnetoencephalographic Functional Methods

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PURPOSE: To compare MR anatomic and magnetoencephalographic (MEG) functional methods in locating the central sulcus. **METHODS:** Eleven healthy subjects and five patients with focal cerebral lesions were studied. The central sulcus was located anatomically with MR by two independent observers using axial vertex and sagittal (midline and lateral) images. Locations via the MEG functional method were based on detecting the somatosensory-evoked magnetic fields elicited by painless tactile stimuli. **RESULTS:** The axial method yielded the most consistent interrater results, with complete agreement in 76% of sections in both control subjects and patients. The intermethod discordance of the sagittal midline and lateral methods was 32% in control subjects and 33% in patients. The concordance of MR and MEG methods ranged from 55% to 84% in control subjects and 65% to 67% in patients. **CONCLUSION:** MR anatomic techniques can usually identify the central sulcus, but in the presence of anatomic distortion, the MEG functional method adds significant information.

Index terms: Brain, sulci; Brain, anatomy; Brain, magnetic resonance; Magnetoencephalography; Magnetic resonance, comparative studies

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Preoperative location of the central sulcus (CS) often plays an essential role in planning the neurosurgical approach and avoiding injury to the primary motor cortex during neurosurgical resections. Although several techniques for identifying the CS on computed tomography (CT) and magnetic resonance (MR) scans have been developed (1–6), there has been very little quantification of the reproducibility of these techniques comparing normal and pathologic conditions. The usefulness of preoperative location of cortical function with magnetoencephalography (MEG) also has recently been described (7, 8). The purpose of this study is twofold: 1) to determine the interobserver reliability of locating the CS in normal and pathologically distorted brains using three different anatomic techniques; and 2) to assess the validity of these anatomic techniques based on their concordance with locations surgically verified via the MEG functional method.

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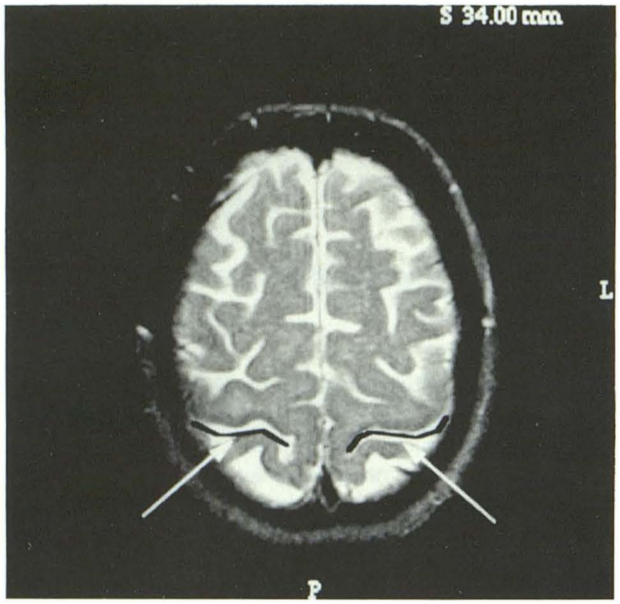
Materials and Methods

Patients

Eleven healthy subjects and five patients with focal cerebral lesions were studied. The control subjects, five men and six women, ranged in age from 30 to 80 years. The five patients, two men and three women, ranged in age from 20 to 71 years. Abnormalities in these five patients included one porencephalic cyst, one astrocytoma, one metastatic lung carcinoma, one meningioma, and one arteriovenous malformation. These five patients were selected to represent a range of anatomic distortion.



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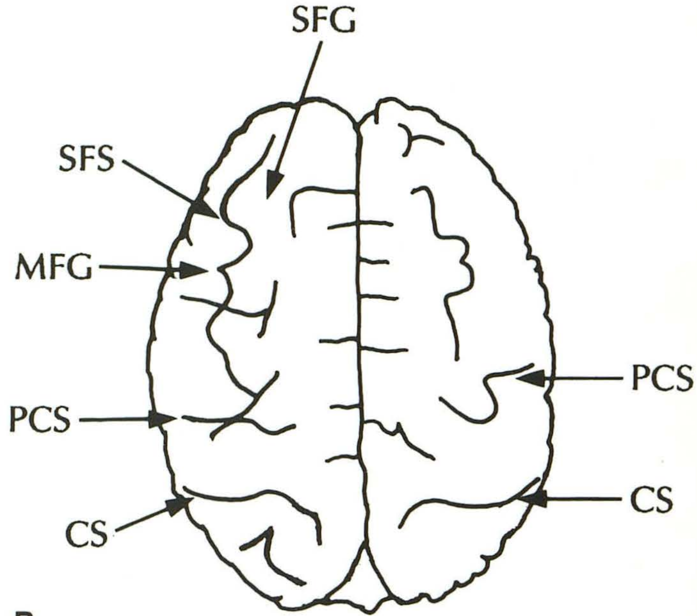

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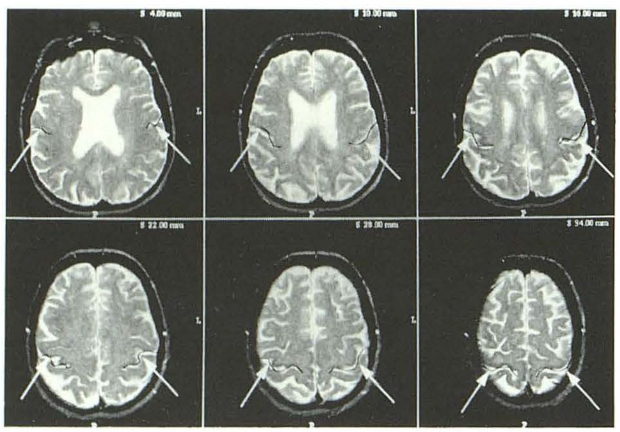

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Fig. 1. Axial anatomic method.

A, Axial vertex section. The superior frontal sulcus courses anteriorly to posteriorly and forms a right angle with the precentral sulcus (*PCS*). The next sulcus posteriorly is the CS (*arrows*).

B, Line drawing of *A*. *SFG* indicates superior frontal gyrus; *SFS*, superior frontal sulcus; *MFG*, middle frontal gyrus.

C, Tracing the course of the CS (*arrows*) on serial axial sections from superior (*bottom right*) to inferior (*top left*).

Anatomic Methods

A 1.5-T MR system was used to obtain spin-echo T1- and T2-weighted axial and T1-weighted sagittal images. Axial scans were obtained parallel to the canthomental line with the isocenter placed on the nasion. The infraorbital line was used in elderly patients with difficulty in cervical flexion. Section thickness was 5 mm with a 1-mm intersection gap. Two observers (DFS and CCG) independently attempted to locate the CS using three different techniques as follows: 1) an axial section through the vertex; 2) a sagittal section through the midline; and 3) a lateral sagittal section through the sylvian fissure. The observers then attempted to trace the CS, along its entire course, on sequential sections from superior to inferior, medial to lateral, and lateral to medial, respectively.

Axial Images

As initially described by Kido using CT (1), the superior frontal sulcus runs from anterior to posterior, separating the superior and middle frontal gyri. Posteriorly, the superior frontal sulcus forms a right angle with the precentral sulcus. The next sulcus posteriorly is identified as the CS (Fig. 1). On images where the CS was difficult to identify because of difficulty in visualizing the right angle formed by the superior frontal sulcus and precentral sulcus, the right angle formed by the superior frontal gyrus and the precentral gyrus was used as described by Iwasaki (2).

Midline Sagittal Images

As described by Steinmetz (3, 6) and then Naidich (5), the cingulate sulcus can be followed in the midline to the vertex where its ascending segment is known as the marginal ramus or sulcus. The notch formed immediately anterior to the marginal ramus at the vertex is formed by the CS (Fig. 2).

Lateral Sagittal Images

On a lateral sagittal section through the sylvian fissure, the anterior horizontal and anterior ascending rami of the

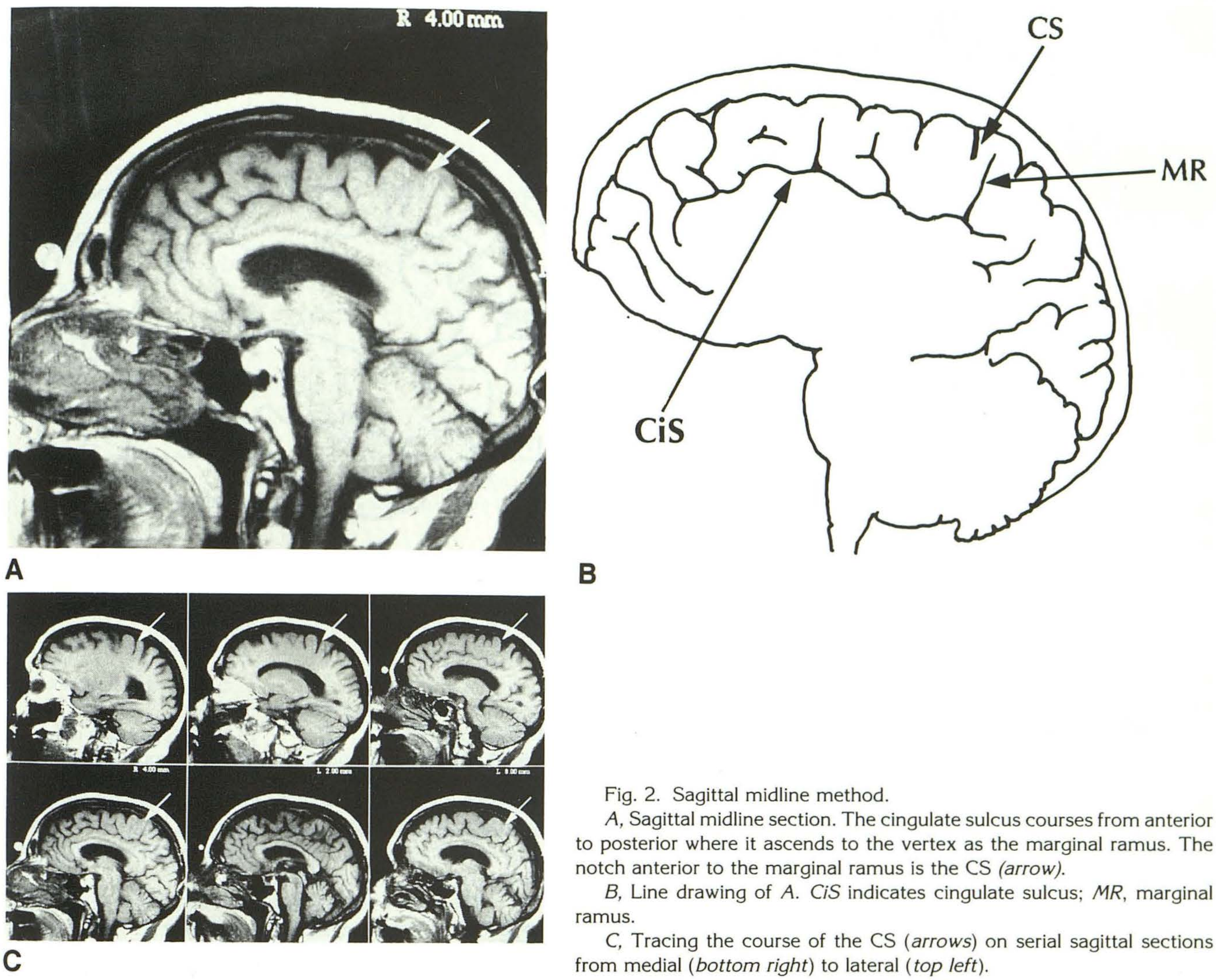


Fig. 2. Sagittal midline method.

A, Sagittal midline section. The cingulate sulcus courses from anterior to posterior where it ascends to the vertex as the marginal ramus. The notch anterior to the marginal ramus is the CS *(arrow).*

B, Line drawing of *A. CiS* indicates cingulate sulcus; *MR,* marginal ramus.

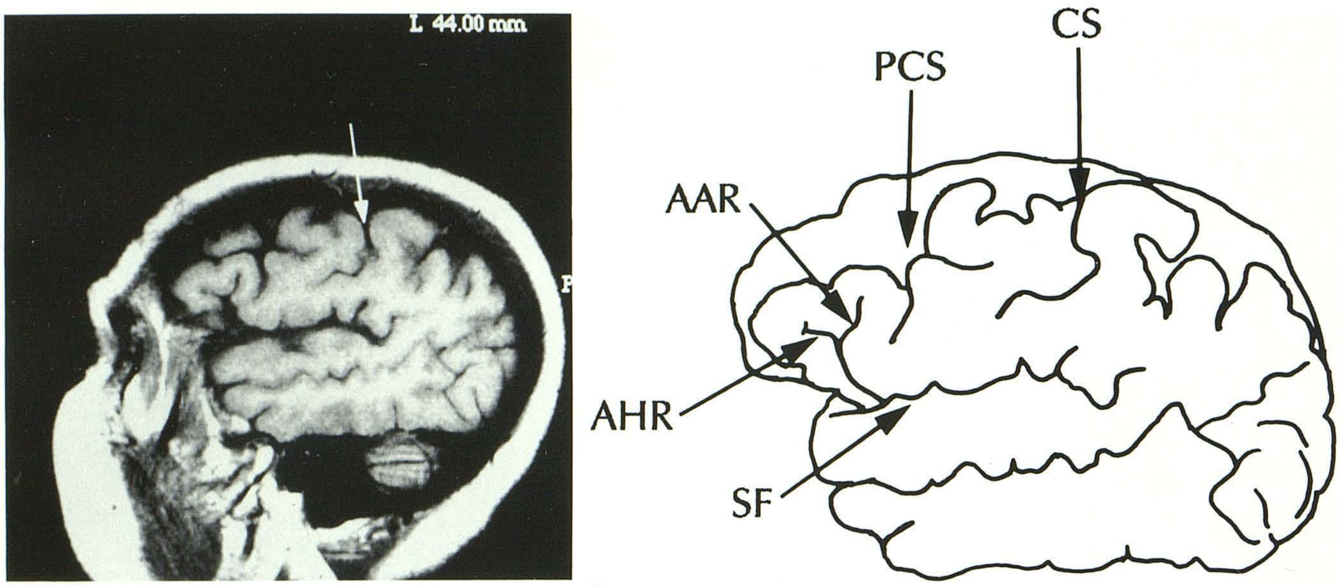
C, Tracing the course of the CS (*arrows*) on serial sagittal sections from medial (*bottom right*) to lateral (*top left*).

inferior frontal gyrus form a Y-shaped appearance, with the sylvian fissure being formed by the pars triangularis and the pars opercularis. The major descending sulcus immediately posterior to the Y or pars opercularis is the precentral sulcus. The next major descending sulcus coursing parallel to the precentral sulcus is the CS (3, 5, 6) (Fig. 3).

MEG Functional Method

Locations via the MEG functional method, also referred to as magnetic source images (MSIs), were obtained with a BTI Magnes 37-channel large-array biomagnetometer (Biomagnetic Technologies Inc, San Diego, CA). Details of this technique have been described previously (9). Painless tactile stimuli were applied to the first, second, and fifth digits and to the lower lip using a pneumatic stimulator. Stimuli-evoked intracranial electric currents, which produced the extracranial somatosensory magnetic fields, were recorded by MEG. An optimal signal-to-noise ratio was selected during the time interval 45 to 75 msec poststimulation, and a single equivalent current dipole model was employed to calculate the magnetic source locations. Neuromagnetic locations were expressed in terms of a cartesian coordinate system based on the nasion and preauricular fiducial points. These fiducial marks were found on the MR scans, allowing transposition of MEG equivalent current dipole locations onto corresponding MR scans of the same patient. The somatosensory-evoked fields identified the postcentral gyrus with the CS lying immediately anteriorly. The sulcus most consistent with the four different somatosensory locations on each side was designated as the CS.

In all five of the patients, the MEG functional locations were confirmed intraoperatively using subcortical recordings of median nerve somatosensory-evoked potentials and/or direct motor stimulation. The intraoperative locations were mapped relative to the pathologic lesion, the midline, and the coronal suture. Upon exposing the brain surface, the lesion was located visually or with ultrasound when necessary. Tags were then placed on the cortical surface over the center of the tumor as well as on the location of the sagittal suture and the intersection of the sagittal and coronal sutures. Somatosensory-evoked loca-



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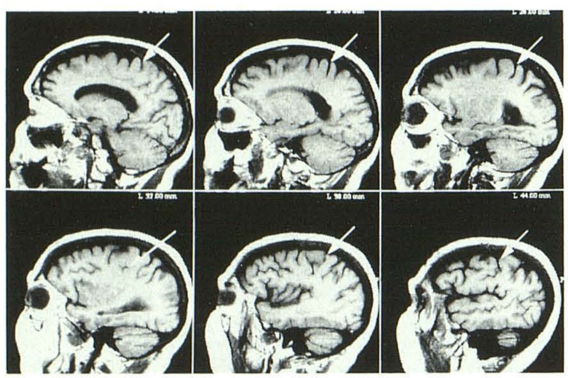

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Fig. 3. Sagittal lateral method.

A, Sagittal lateral section. The anterior horizontal ramus and anterior ascending ramus of the sylvian fissure form a Y-shaped appearance with the fissure anteriorly. The next major descending sulcus posteriorly is the PCS; the major descending sulcus after that is the CS (*arrow*).

B, Line drawing of *A. SF* indicates sylvian fissure; *AHR*, anterior horizontal ramus; *AAR*, anterior ascending ramus.

C, Tracing the course of the CS (*arrows*) on serial sagittal sections coursing from lateral (*bottom right*) to medial (*top left*).

tions were recorded from strip corticography electrodes with 1-cm interelectrode distances. Median nerve stimulations were made at 4.7 stimuli/sec (n = 124 repetitions), locating the N19/P21 complex phase reversal. The location of the median nerve phase reversal was then tagged. Direct motor stimulation was done in four of five surgical cases with a 200 μsec duration at 60 Hz. The operating surgeon then identified the CS as that sulcus immediately anterior to the gyrus showing median nerve phase reversal. The surgeon was thus able to determine the relationship between the location of the CS and the posterior or anterior margin of the lesion. This distance was measured along with the distances from the sagittal and coronal sutures. Comparisons of the surgical locations with the MSI and MR locations were based on the relationship of the CS to the margin of the lesion in closest proximity.

To determine the reproducibility of the three anatomic techniques, the discordance between the two independent raters was calculated according to the number of sulci of disagreement for each section-by-section comparison in both the control subjects and the patients (Table 1). In order to determine the discordance between the two different sagittal techniques, intrasubject comparisons between the two techniques were made for each patient and the results for the two raters combined.

In order to determine the validity of the MR anatomic locations, the MR anatomic and MEG functional locations were then compared. The MEG was taken as a standard of reference in the patients, having been confirmed in all five of these patients intraoperatively. In the 11 control subjects, there was no direct standard, since these patients did not undergo surgery, hence MEG functional locations were used as the standard of comparison.

Results

Results of the axial and sagittal interobserver comparisons are summarized in Table 1, the sagittal midline versus sagittal lateral intrasubject comparisons in Table 2, and the MR anatomic versus MEG/MSI functional comparisons in Table 3.

MR Anatomic Methods

Of the three different anatomic methods, the axial yielded the most consistent results, with

TABLE 1: Interrater discordance (number of sulci)

	0 (Same)	1 Sulcus	2 Sulci	≥3 Sulci
Sagittal lateral method				
Control subjects	79 (50%)	63 (40%)	13 (8%)	3 (2%)
Lesion patients	65 (66%)	29 (29%)	0 (0%)	5 (5%)
Sagittal midline method				
Control subjects	116 (69%)	51 (30%)	1 (<1%)	0 (0%)
Lesion patients	49 (67%)	20 (27%)	2 (3%)	2 (3%)
Axial method				
Control subjects	97 (76%)	27 (21%)	3 (2%)	0 (0%)
Lesion patients	55 (76%)	9 (13%)	2 (3%)	6 (8%)

Interrater comparisons: discordance in number of sulci using section-by-section and side-by-side comparisons. Three methods are compared.

TABLE 2: Intermethod discordance midline versus lateral (number of sulci)

	0 (Same)	1 Sulcus	2 Sulci	≥3 Sulci
Subjects				
Control subjects	225 (68%)	92 (28%)	12 (4%)	1 (<1%)
Lesion patients	97 (67%)	32 (22%)	3 (2%)	12 (8%)

Intrasubject comparisons for each rater. Entries are discordances in number of sulci using section-by-section and side-by-side comparisons of lateral with midline location methods.

TABLE 3: Discordance MEG versus MR (number of sulci)

	0 (Same)	1 Sulcus	2 Sulci	≥3 Sulci
Sagittal lateral method				
Control subjects	56 (64%)	27 (31%)	5 (6%)	0 (0%)
Lesion patients	36 (67%)	12 (22%)	1 (2%)	5 (9%)
Sagittal midline method				
Control subjects	38 (55%)	18 (26%)	13 (19%)	0 (0%)
Lesion patients	37 (66%)	14 (25%)	2 (4%)	3 (5%)
Axial method				
Control subjects	66 (84%)	13 (16%)	0 (0%)	0 (0%)
Lesion patients	48 (65%)	13 (18%)	5 (7%)	8 (11%)

Comparisons between functional MEG and anatomic MR methods. Cell entries are discordances in number of sulci using section-by-section and side-by-side comparisons.

complete agreement (no sulcal difference) in 76% of sections compared in the control subjects and in 76% of those in the patients; in 24% of sections, there was disagreement by at least one sulcus (Table 1). The sagittal midline method yielded complete agreement in only 50% of sections in the control subjects, but in 66% in the patients. The two sagittal methods agreed within the same patient in 68% of sections in the control subjects and in 67% of those in patients with lesions (Table 2).

T1- and T2-weighted images were felt to be equally useful for locating the CS. T1-weighted images were most commonly obtained in the sagittal plane and T2-weighted images in the axial plane.

MR Anatomic versus MEG Functional

Of the three MR anatomic methods, the axial was most often in concordance with MEG: agreement was present in 84% of sections in the control subjects but decreased to 65% in the patients (Table 3; Figs. 4 and 5). Furthermore, in 11% of the sections in patients, either the CS could not be identified at all because of anatomic distortion, or there was disagreement by at least three sulci (Fig. 4).

The sagittal lateral method agreed with MEG in 64% and in 67% of sections in the control subjects and in the patients, respectively. The sagittal midline method agreed with MEG in 55% and in 66% of sections in control subjects and in patients, respectively.

In the five patients, variable degrees of anatomic distortion were present. A large left hemispheric porencephalic cyst in one patient caused severe anatomic distortion, making it impossible to locate the CS by anatomic methods on nearly all sections (Fig. 4). From the somatosensory location by MEG, the motor cortex was inferred to be wrapped around the cyst posteriorly and superiorly. This inference was confirmed at operation by direct motor stimulation. Additionally, the MEG detection of slow wave activity helped to direct the intraoperative electroencephalogram and plan the surgical resection of epileptogenic brain parenchyma adjacent to the cyst wall, which was successful in markedly reducing this patient's seizure activity.

In the patient with a left frontal cystic astrocytoma, moderate gyral distortion was present locally in the region of the rolandic cortex. The CS could be located away from the tumor, but in the region of the mass there was greater uncertainty reflected in interrater discordance. MEG accurately identified the CS adjacent to the tumor as was confirmed by intraoperative corticography and stimulation (Fig. 6).

Only mild anatomic distortion was present locally in the patient with a small right anterior

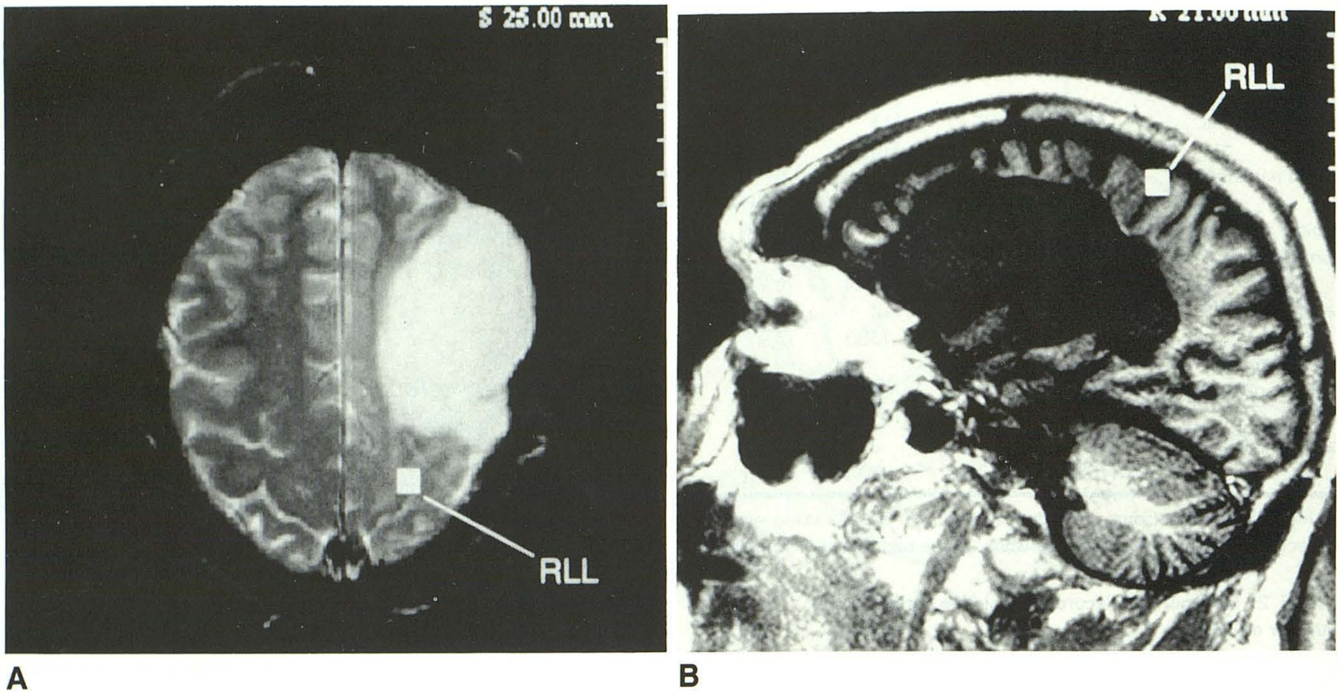


Fig. 4. Large left porencephalic cyst.

A, Axial T2-weighted image.

B, Sagittal T1-weighted image. The location of the CS and precentral gyrus could not be identified by anatomic methods alone because of gross anatomic distortion. The MEG-detected equivalent current dipole sources after repetitive stimulation of the right lower lip (*RLL*) are shown. From the somatosensory location by MEG, the motor cortex was inferred to be wrapped around the cyst posteriorly and superiorly immediately anterior to the primary somatosensory cortex. This inference was confirmed at operation by direct motor stimulation.

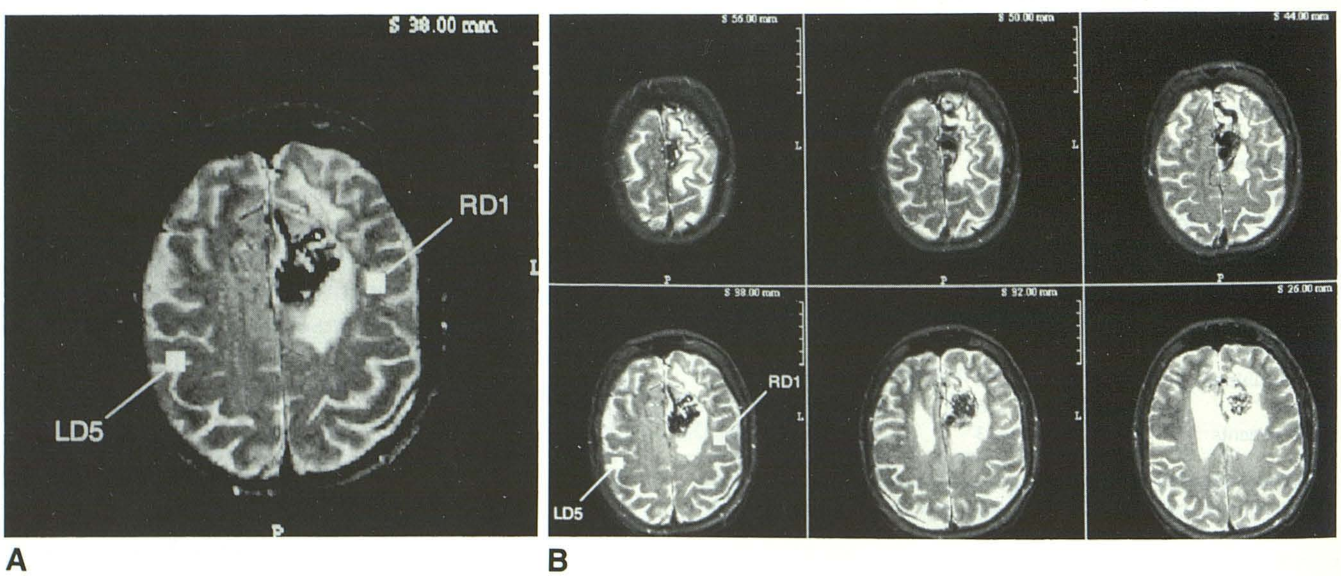


Fig. 5. Left frontal arteriovenous malformation.

A, Axial T2-weighted image. *RD1* indicates the MEG-detected equivalent current dipole source after stimulation of the right first digit (of the hand); *LD5*, after stimulation of the left fifth digit. Note the LD5 agrees with the anatomic location in the right hemisphere, whereas the RD1 is more anterior in the left hemisphere than expected. At surgery, the RD1 location was confirmed by electrocorticography.

B, Series of axial T2-weighted images descending from *top left* to *bottom right*.

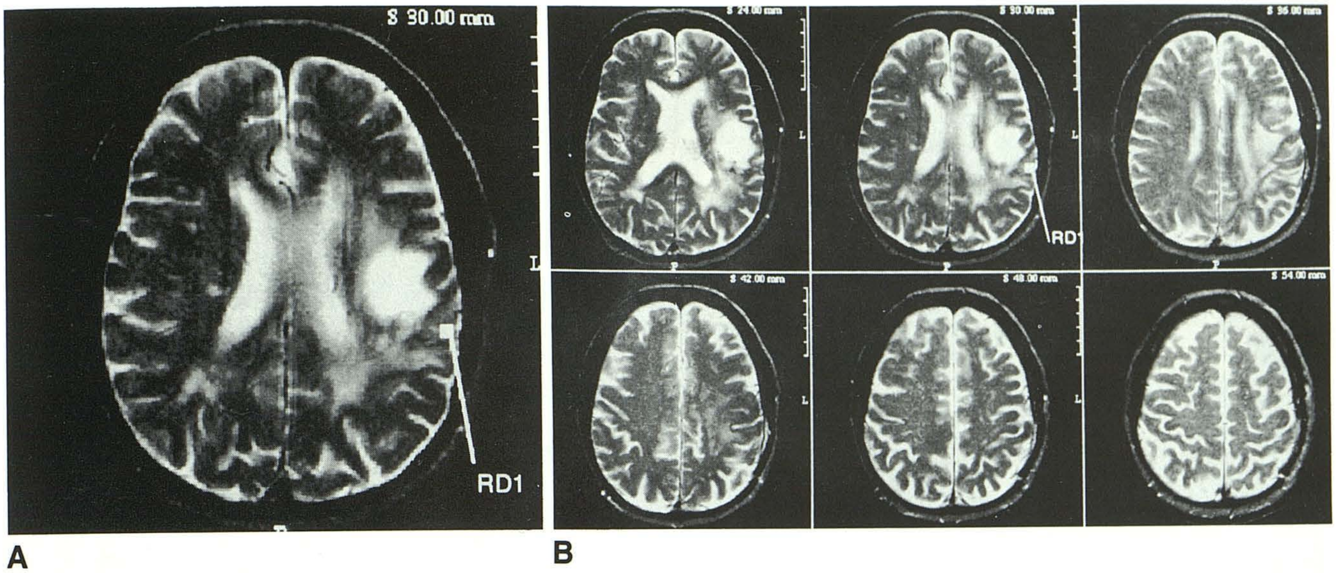


Fig. 6. Left posterior frontal cystic astrocytoma.

A, Axial T2-weighted image. *RD1* shows location of the somatosensory-evoked field after stimulation of the right first digit. This placed the CS immediately posterior to the mass as was confirmed at operation. The anatomic techniques generally placed the CS 1 sulcus more anteriorly at this level.

B, Series of T2-weighted axial images ascending from *top left* to *bottom right.*

parietal lobe lung metastasis (Fig. 7) and no significant gyral distortion in the patient with a parafalcine meningioma (Fig. 8). In both of these patients, the interrater concordance of locations was similar to that of the control subjects. The anatomic locations generally agreed with the surgically confirmed MEG functional CS identifications.

In the patient with a large left frontal arteriovenous malformation (Fig. 5), MR and MEG were in agreement on the normal side. On the side with the arteriovenous malformation, MEG placed the somatosensory cortex far anteriorly, whereas the MR anatomic method placed the CS more posteriorly in a symmetric position with the opposite hemisphere. These disparate results were obtained despite the absence of gross anatomic distortion. At operation, the MEG functional location was confirmed.

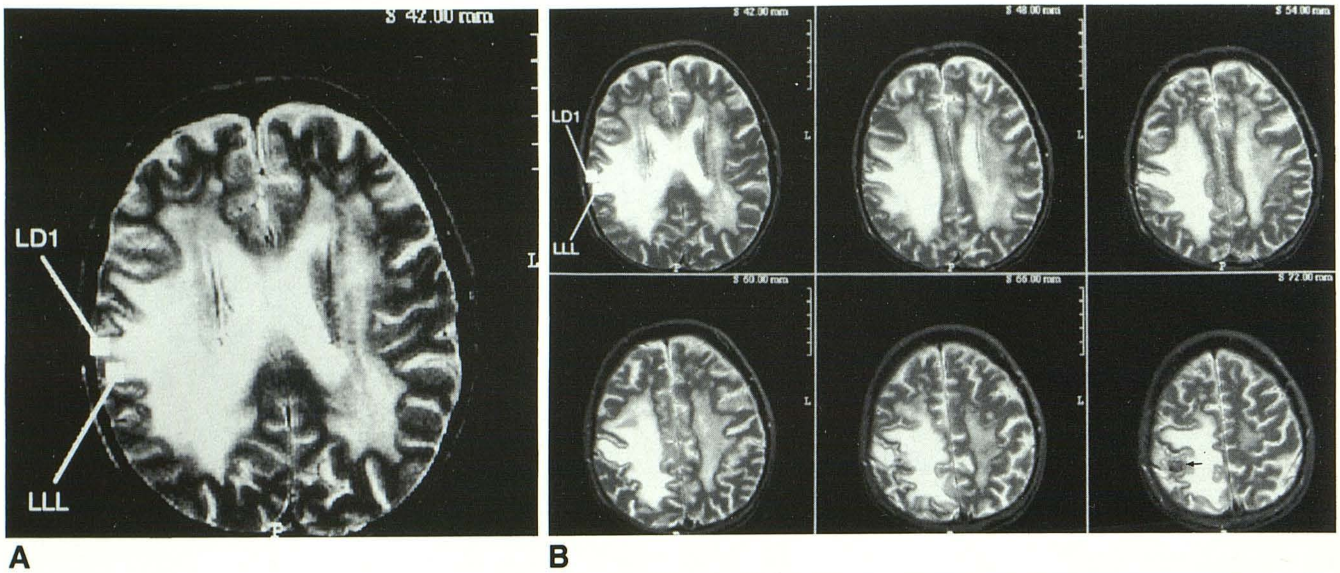
We have no definite explanation for this disparity but can only hypothesize that the arteriovenous malformation represents a developmental malformation and was, therefore, associated with a developmental variation or cortical reorganization of the location of motor and sensory functions.

Discussion

Our results show that in the absence of anatomic distortion, the CS usually can be located on a single vertex axial, sagittal midline, or lateral section through the sylvian fissure using MR anatomic methods. Tracing the CS through the remainder of the hemisphere, however, is not a trivial task and may result in a 24% to 50% error rate as shown by our interobserver comparisons (Table 1). Although computer tracing, cine modes, and three-dimension volume acquisitions allowing for 1-mm section spacing may facilitate tracking of the CS from section to section, such methods are time-consuming, and the reproducibility of these techniques needs to be confirmed by interobserver comparisons and their accuracy confirmed by either intraoperative or gross anatomic studies.

The anatomic techniques used in this study are useful but have not been validated by a combination of interobserver rating and operative confirmation. Kido (1) reported on use of the axial technique with CT and was able to identify the posterior margin of the superior frontal gyrus and its relationship to the precentral sulcus and the CS in 92 hemispheres of 50 patients. No attempt to trace the CS on adjacent sections and no interobserver comparisons were made.

Steinmetz (3) identified and traced the CS in 40 hemispheres of 20 patients using both the sagittal and midline techniques used in our studies. No interobserver comparisons were made. Naidich (5) described similar sagittal techniques



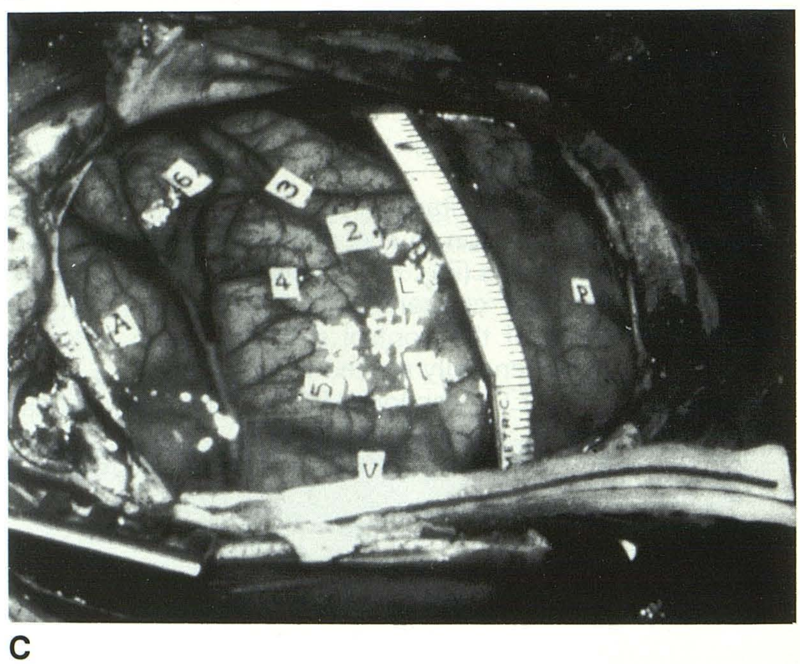


Fig. 7. Right anterior parietal lobe lung metastasis.

A, Axial T2-weighted image. *LD1* and *LLL* show MEG locations of the somatosensory-evoked fields for the left first digit and left lower lip, respectively. Bilateral periventricular T2-weighted increased signal is due to prior radiation therapy. There is more subcortical and cortical edema because of a small right parietal lobe metastasis present more superiorly. Note the diffuse edema causes no significant gyral displacement.

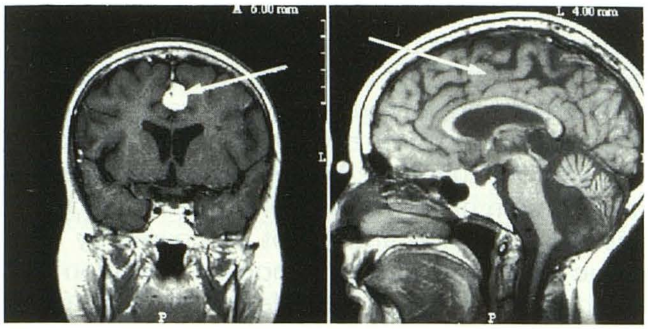
B, Series of axial T2-weighted images ascending from *top left* to *bottom right.* Low signal metastasis is indicated by *arrow* in *bottom right* image.

C, Intraoperative photograph. *L* indicates the location of the tumor found by intraoperative ultrasound. Tag *3* indicates the sensory gyrus located by intraoperative-evoked responses. Tags *4–6* indicate the motor cortex. *A* indicates anterior; *P,* posterior; and *V,* vertex. The *ruler* in the field was used to verify the location of median nerve reversal relative to the tumor and skull landmarks.

to those of Steinmetz but gave no quantification of results and did not study interobserver reproducibility.

Iwasaki (2) compared identification of the CS by the pattern of medullary branching of the cerebral white matter with identification by tracing the CS from superior to inferior on axial CT sections of 104 healthy subjects and 9 patients with space-occupying lesions and cerebral angiograms. This technique is very similar to that described by Kido with the difference being that it focuses on the medullary pattern of the gyri, whereas the Kido technique focuses on the sulci, which form the outline of the gyri. It is complementary to the Kido technique and is most useful when the sulci are effaced or difficult to visualize. Iwasaki described the medullary branching pattern as useful and implied a 100% identification rate but did not give a clear breakdown of his results and did not describe any interobserver comparisons.

Berger (4) identified the CS as a "mirror image of distinctly transverse sulci" on vertex axial MR sections. The marginal ramus of the cingulate sulcus was used to identify the CS on midline sagittal sections; a perpendicular line drawn to the posterior roof of the insular triangle was used on lateral sections. Results were correlated with intraoperative electrocorticography in nine of his patients. The axial technique was found to be



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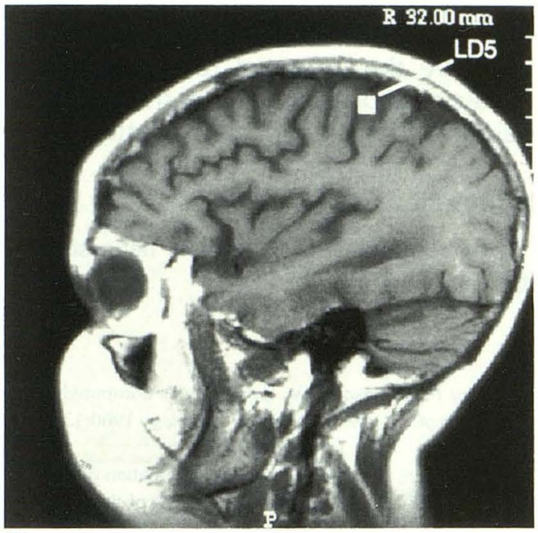

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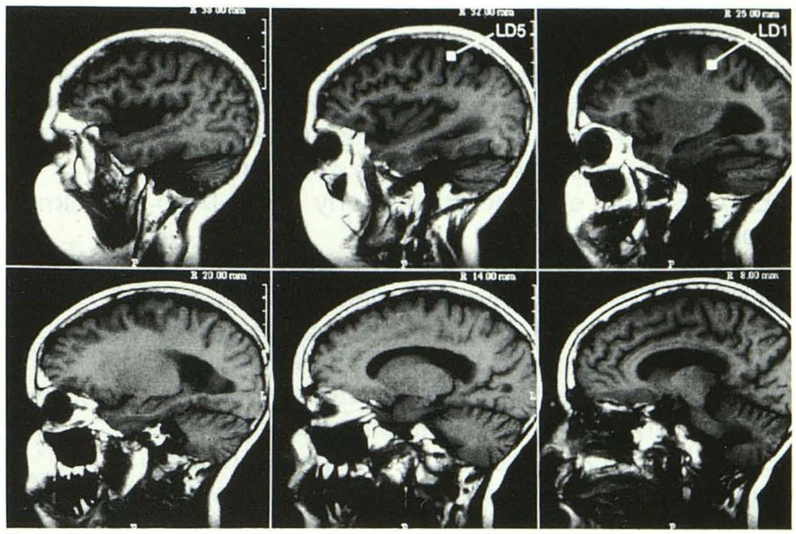

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Fig. 8. Parafalcine meningioma.

A, Coronal contrast-enhanced and sagittal noncontrast T1-weighted images show a left parafalcine meningioma (*arrow*).

B, Sagittal T1-weighted image.

C, Series of sagittal images coursing from lateral (*top left*) to medial (*bottom right*).

LD1 (*C*) and *LD5* (*B* and *C*) are the detected positions for the evoked fields after stimulation of the left first and fifth digits. The meningioma is more midline and did not cause significant distortion in the region of the rolandic cortex. The CS was identified as the sulcus immediately anterior to the LD1 and LD5 locations as was confirmed intraoperatively. Dilatation of the fourth ventricle is secondary to prior resection of a cerebellar astrocytoma.

accurate in all nine of his patients; the sagittal methods were reported to be less accurate for locating the CS but were able to identify the rolandic cortex. No quantification of their results was given, nor were attempts to trace the CS from section to section reported. In our experience, the axial location method reported by Berger identified the same sulcus that we identified in most patients but proved to be less reliable and, in some cases, to lead to erroneous conclusions.

Sulcal distortion associated with a mass lesion often precluded accurate anatomic location in our patient sample, as might be expected from clinical experience and research studies. Displacement of the rolandic cortex is known to occur in patients with neoplasms (10). Perhaps of paramount importance, anatomic techniques do not account for topographical variations in the loci of motor function. Cortical variations in the location of motor and sensory function have been demonstrated in humans (10, 12) and in animals (13). To our knowledge, it is not known exactly how often these cortical variations occur. We do know, for example, that Penfield (10) reported sensation in the hand, arm, or shoulder at 279 points of cortical stimulation, 91 of which (32%) were precentral and 188 (68%) postcentral. He found similar results with motor responses with 36 of 222 points yielding upper-extremity movement being postcentral and the remainder precentral (10). It is not known how often these trans-rolandic responses to direct cortical stimulation may have been the result of excitation of a neuronal chain or network crossing the CS. In addition, it is known that direct stimulation of the same cortical point in different individuals will commonly yield different responses but that the motor and somatosensory homuncular relationships are invariant (10, 12). Similar variations to those described for motor and sensory function are also known to occur with the centers for speech (14, 15). For these reasons, functional methods such as electrocorticography are necessary in surgery to identify motor and somatosensory cortex.

MEG/MSI, like electrocorticography, directly locates neurologic function independent of any anatomic distortion, with the added advantages of noninvasive measurement, allowing assessment and planning prior to craniotomy. Studies with healthy subjects have shown that somatosensory identifications are highly repeatable and reliably locate the postcentral gyrus (16). In addition, in clinical cases with MEG/MSI, it is possible to compare somatosensory functional locations on the affected and unaffected hemispheres as an additional guide for the neuroradiologist in tracing sulci. Most importantly, by using electrocorticography as the standard of reference, MEG/MSI accurately identified the CS in each of the five surgical patients in our series. To date, an additional 10 patients, not included in this study, have had operative confirmations of MEG/MSI functional locations with no cases so far in which MEG/MSI and electrocorticography have been inconsistent.

Orrison (8) recently reported two patients in whom MEG/MSI showed displacement of the sensorimotor cortex by neoplastic disease, one anteriorly and one posteriorly. In both cases, the neurosurgeon altered his operative approach based on the MEG/MSI locations, leading to an excellent clinical outcome. Preliminary results suggest that MEG/MSI identification of slow wave activity that is associated with mass lesions also may prove useful in preoperative identification of dysfunctional and, therefore, presumably nonvital areas of adjacent cortex (17, 18).

Although intraoperative electrocorticography and direct motor stimulation confirmed primary motor function to be located immediately anterior to primary somatosensory function, work is ongoing to identify primary motor cortex directly with MEG/MSI.

MEG/MSI has been limited in the current study to the location of only a part of the length of the somatosensory cortex extending from the location of the lower lip to the first, second, and fifth fingers. However, MEG/MSI has the potential to map out the entire sensory homunculus, and such work is ongoing. This, together with the cross-check of motor functional mapping in MEG/MSI, will represent a major advantage of functional as opposed to purely anatomic mapping.

In conclusion, in the absence of anatomic distortion, MR anatomic techniques usually allow identification of the CS on a vertex axial, sagittal midline, or parasagittal lateral section. Attempts to trace the CS on each section through the hemispheres may lead to errors in location. Anatomic distortion caused by a mass lesion makes accurate location much more difficult (and in some patients impossible) using anatomic methods solely. Of equal importance, these anatomic methods do not account for topographical variations in the location and organization of motor and sensory function. MEG/MSI produces accurate location of somatosensory and motor cortex based on function and is not hampered by anatomic distortion or topographical variation. Indeed, MEG/MSI may provide evidence for functional reorganization which would otherwise be discovered only intraoperatively if at all. MEG functional and MR anatomic methods used in conjunction have the potential to play a major role in neurosurgical planning and in the resection of mass lesions and vascular malformations.

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