Noninvasive Preoperative Cortical Localization by Magnetic Source Imaging

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Summary: The authors successfully used magnetoencephalography and MR data to localize the sensorimotor cortex in two patients prior to neurosurgery; preoperative localization influenced surgical management.

Index terms: Magnetoencephalography; Super conducting quantum interference device (SQUID); Surgery, guidance/planning

Localization of cortical activity is important in surgical planning for the approach and treatment of neoplasms, vascular malformations, and epilepsy (1). At present direct physiologic assessment (using intraoperative stimulation or recording techniques) is necessary to accurately identify cortical function because direct visual anatomical identification may be inaccurate (1–4).

The accuracy of electrical (EEG) and magnetic (magnetoencephalography (MEG)) recordings in the preoperative localization of the hand sensorimotor cortex has been compared to intracerebral recordings in patients with complex partial seizures (1). We report the success of magnetic source imaging (MSI) using the combined techniques of MEG and magnetic resonance (MR) in the noninvasive preoperative localization of the hand sensorimotor cortex for surgical guidance in two cases.

Subjects and Methods

Two patients were evaluated preoperatively by MSI. Both subjects completed an informed consent and were evaluated according to Human Research Review Committee-approved protocol. MEG was performed in a magnetically shielded room with a 7-channel neuromagnetometer (Biomagnetic Technologies Inc, San Diego, CA). The neuromagnetometer consisted of superconducting quantum interference devices (SQUID) and seven superconducting gradiometer detection coils immersed in a bath of liquid helium housed within a Dewar. The detection coil system monitoring the patient's cerebral biomagnetic fields were inductively coupled to the SQUIDs. The magnetic flux changes within the SQUID were monitored by electronics located outside the Dewar, which also provided signal amplification. The detection coils were second-order gradiometers with coil diameters of 1.8 cm and baselines of 3.98 cm. The seven gradiometers were fixed within the Dewar in an evenly spaced hexagonal pattern with one gradiometer in the center of the hexagon. The hexagon was 6 cm across and the center of each coil was spaced 2 cm from the center of each adjacent coil. The Dewar was positioned within 3 to 4 mm of the patient's head during recordings.

For each patient both median nerves were stimulated at the wrist with a 200 microsecond electrical pulse at 4 pulses per second and at an intensity that produced definite thumb and index finger movement, but that was still tolerable to the patient. The median nerve was selected because of the ease of stimulation, and the central homunculus location of the hand. The magnetic field of the cortical response to the somatosensory stimulation was recorded by positioning the Dewar over the side of the head contralateral to the wrist that was stimulated. In order to adequately map the magnetic field, the Dewar was placed at three to four positions over the normal side of the head and at seven to nine positions over the side of the head with the intracranial mass lesion. The position of the Dewar relative to fixed-surface landmarks on the patient's head was determined with a 3-D digitizer (Biomagnetic Technologies; and Polhemus, Colchester, VT). At each Dewar position, the contralateral wrist was stimulated 100 times and the magnetic field was measured at a sampling rate of 1000 Hz for 50 msec before the stimulus and 200 msec following the stimulus with a high pass filter of 0.1 Hz and a low pass filter of 500 Hz. The 100 recordings were

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averaged and filtered with a high pass of 2 Hz and low pass of 200 Hz with a 12 dB/octave drop-off. The magnitude of the magnetic N20 cortical response was measured for each of the sensors at each of the Dewar positions. Magnetic-field maps were constructed from these magnitudes.

The patients were scanned on two 1.5-T superconducting MR systems. The scan parameters provided T1- and T2-weighted images pre- and post-gadolinium infusion. On one scanner, images were performed with 5-mm slices and 2.5-mm gaps in the sagittal, coronal, and axial planes. Spin-echo T1 (800/20-TR/TE), proton density (2800/TE), and T2-weighted images (2800/100) were obtained. On the second scanner, imaging parameters were T1 (600/15), T2 (2500/90), and proton density (2500/22) sequences pre- and post-gadolinium with 5-mm thick slices and 2-mm gaps in the sagittal, axial, and coronal planes. In addition, a 3-D FLASH imaging sequence (20/5/40°-TR/TE/flip angle) was used to acquire data (256 × 256 × 128) sagittally throughout the entire head over a cube of 256 mm on a side. The reconstructed image data had an in-plane resolution of 1 mm and a depth resolution of 2 mm.

For the 3-D acquisition, skin markers (vitamin E capsules) were placed at the same surface landmarks that were used for the MEG recordings. The markers were placed at the nasion and at the preauricular creases of both ears.

In order to map the MEG source locations to the MR image data, the MEG coordinate system must be related to that of the MR data. The MEG coordinate system is defined as having an origin midway on the line between the right and left ear markers and having the x-axis passing through the nasion marker. The MEG y-axis is in the plane defined by three markers and is perpendicular to the x-axis. The MEG z-axis is then normal to the xy plane.

The multiplanar reconstruction facility of the imager was used to position a reference plane through the image data such that the three markers were coplanar (Fig. 1). The MEG origin and xy axis were identified in this reference image, and a parallel series of 1-mm thick slices were formatted from the cube of MR data. The pixel corresponding to the MEG xy coordinates could thus be identified in each reformatted slice and the MEG z coordinate determined which slice contained the source location.

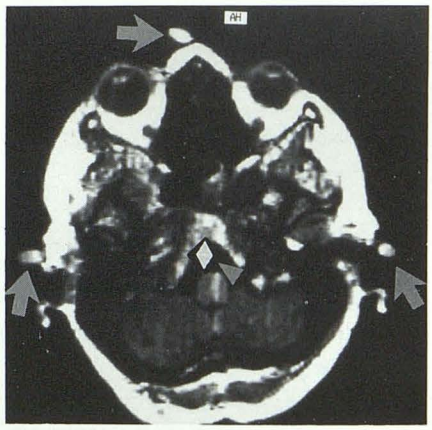

Fig. 1. Case 1. Axial reconstructed MR (20/5/40°-TR/TE/flip angle) at 1-mm slice thickness through the plane of MEG markers (*arrows*). The center of the *diamond* (*arrowhead*) is the designated center of the head for MEG x, y, and z coordinates. Locations of sensorimotor function are calculated from this plane and head center identification (see Figs. 2 and 3).

The system provides physical positions from the MR pixel/slice locations and these were used to place the MEG source in conventional transverse, sagittal, and coronal planes from the original MR data (Figs. 2A–2F).

In the second case, calculations were obtained from the regions of the nasion and tragus of the ear from the MR images without markers. The approximate locations of the hand on the motor cortex were identified on the normal and abnormal sides prior to surgery (Fig. 3). 3-D acquisition MR imaging, including placement of surface markers and reconstruction of the images, required approximately 45 minutes. The MEG data collection, using the 7-channel system, required approximately 90 minutes for each hemisphere. The total time required to produce the collage, or MSI, was approximately 4 hours for both hemispheres. No cortical intraoperative monitoring was performed.

Case Report

Case 1

A 72-year-old, right-handed woman presented with a 3-week history of generalized throbbing headaches and left arm dysfunction. On admission, the patient was alert and oriented. The patient had a mild left hemiparesis involving her left arm and hand more than the face and leg. She performed poorly on tests of graphesthesia, stereognosis, and double simultaneous tactile stimuli when the stimulus involved the left hand. The patient's visual fields were intact to bedside testing with one stimulus, but she did not detect the left visual field stimulus when stimuli were presented to both visual fields. Deep tendon reflexes were normal bilaterally and both plantar responses were flexor.

Contrast-enhanced CT and the MR with gadolinium demonstrated a large right parietotemporal mass with surrounding edema and midline shift, and an irregular rim of contrast enhancement. The patient underwent a localization procedure for hand function by MEG (Fig. 4). A volume acquisition MR with surface markers was performed for correlation with the MEG demonstrating anterior displacement of the sensorimotor cortex (Fig. 2). Intraoperative ultrasound was used to localize the mass and direct the neurosurgeon away from the identified sensorimotor cortex. Postoperative neurologic examination showed no deterioration in left arm and leg strength and no changes on the sensory exam. Pathologic confirmation of the surgical specimen revealed glioblastoma multiforme.

Case 2

A 39-year-old, right-handed woman presented with a 7-month history of left upper extremity weakness and "heavy" sensation, 1-month history of left lower extremity weakness with difficulty walking, and headaches. Physical examination revealed marked left spastic hemiparesis af-

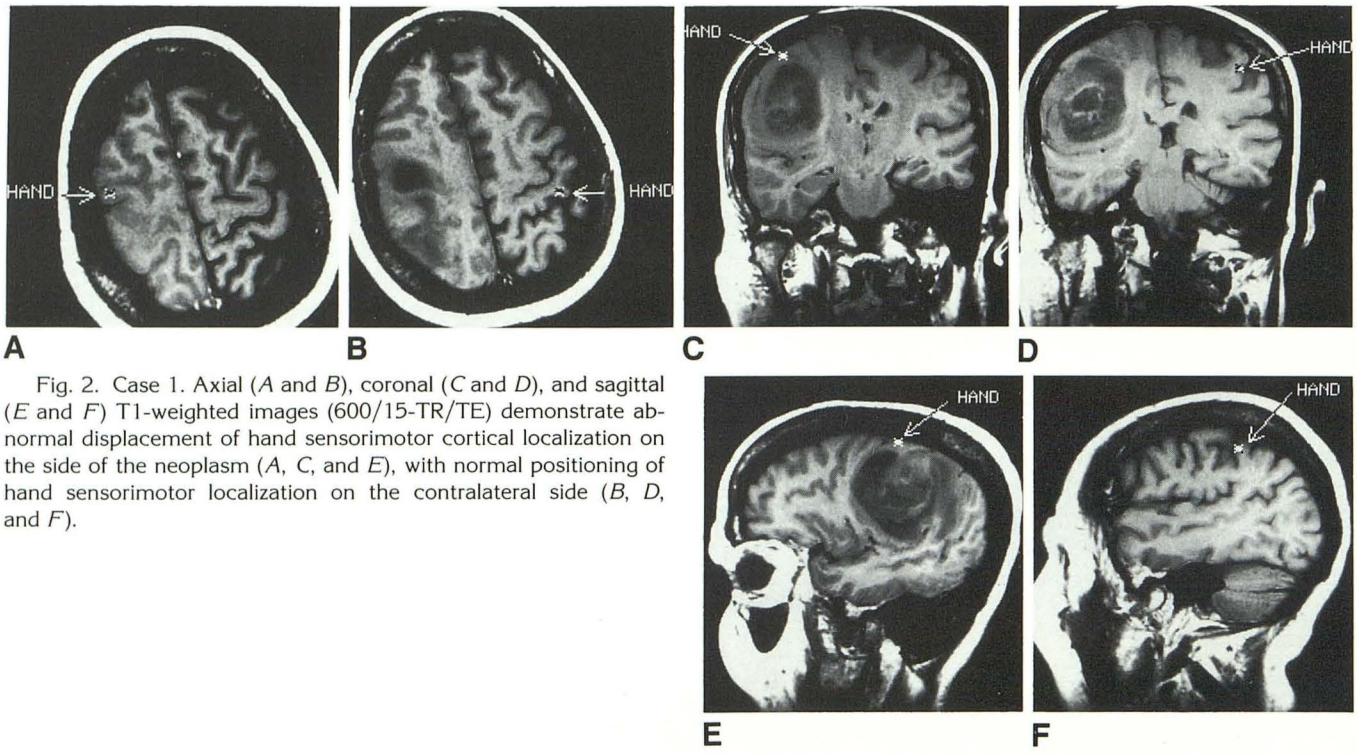

Fig. 2. Case 1. Axial (*A* and *B*), coronal (*C* and *D*), and sagittal (*E* and *F*) T1-weighted images (600/15-TR/TE) demonstrate abnormal displacement of hand sensorimotor cortical localization on the side of the neoplasm (*A*, *C*, and *E*), with normal positioning of hand sensorimotor localization on the contralateral side (*B*, *D*, and *F*).

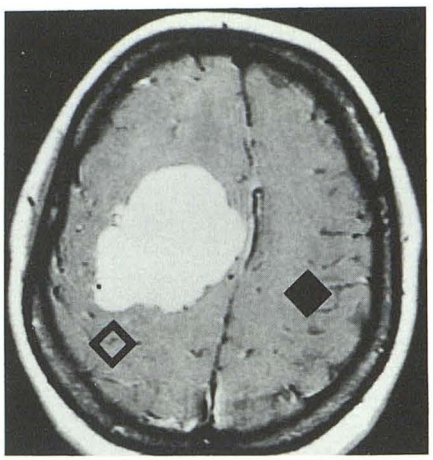

Fig. 3. Case 2. Axial T1-weighted MR post-gadolinium (800/20-TR/TE) images demonstrate normal position of hand sensorimotor localization on the left (*solid diamond*) and abnormal posterior displacement of the sensorimotor localization of the hand on the right (*open diamond*). The actual sensorimotor localization on the right was also displaced superiorly, and the approximate position is identified here for direct comparison with the normal side.

fecting arm and leg equally and, to a lesser extent, the face. Papilledema was present bilaterally.

MEG was performed prior to surgery with localization of hand function bilaterally. This was correlated with the MR which demonstrated an intensely enhancing 5-cm mass in the right frontal parietal region (Fig. 3). The magnetic-field pattern was displaced posteriorly relative to this intracranial mass lesion (Fig. 5). From the displacement of the sensory response, we predicted that motor cortical function was also displaced posterior to the mass lesion. At surgery, a mildly vascular benign meningioma based on the convexity dura adjacent to the superior sagittal sinus was found. Special care was taken to preserve the cortex posterior to the tumor. Postoperative course was uneventful. There was rapid improvement of her hemiparesis with return to normal function by 2 weeks postsurgery.

Discussion

The early studies of somatic motor and sensory representation in the cerebral cortex demonstrated variations in normality. A single cortical stimulation was noted to produce both sensation and movement in a body part (5). Variations in the location of the sensory motor function over the cortex have also been identified (2, 5). The close proximity of both sensory and motor function on the cortex may make it difficult to sort out the exact location of sensory or motor function in a given individual, regardless of the modality employed. However, it is clear that precentral and postcentral convolutions represent the sensorimotor Rolandic function and that identification of variations may have important research and clinical applications. Such variability in the position on the central gyri of body parts has also been demonstrated in animals (2, 6).

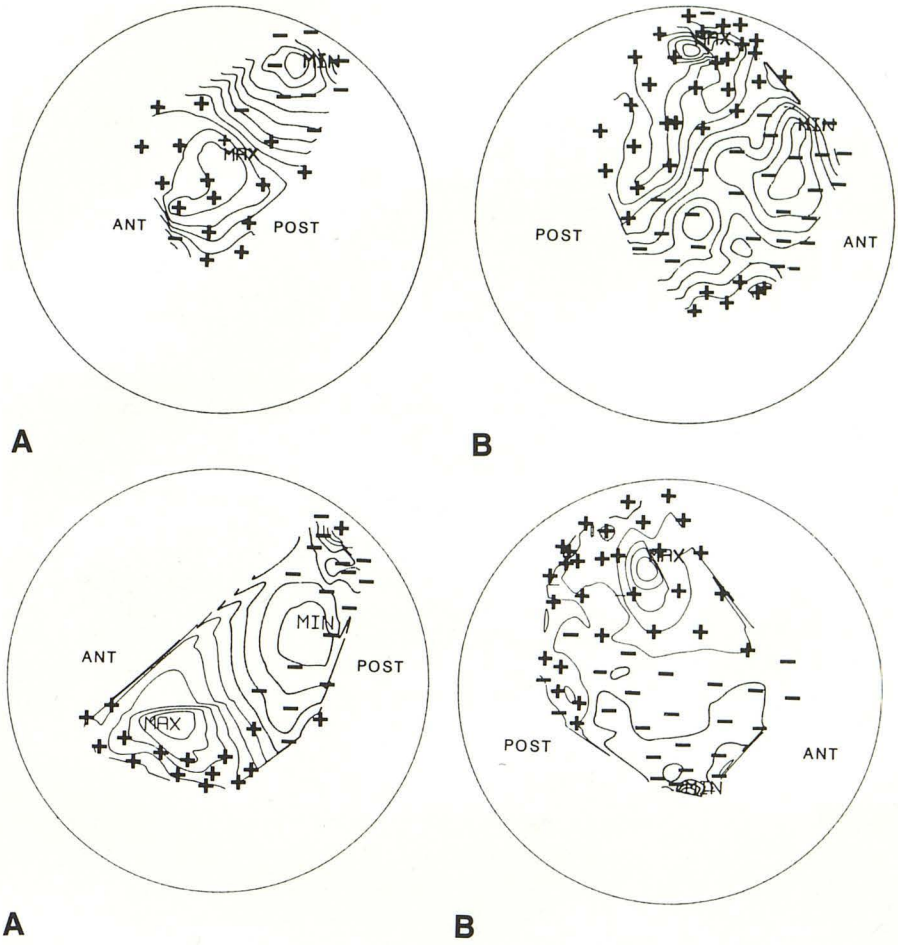

Fig. 4. Case 1.

A, Magnetic-field map of the somatosensory response recorded over the left (normal) side of the head in patient 1. The viewing angle for this and the subsequent magnetic-field maps were optimized to show both positive and negative magnetic activity but are not necessarily the same for all four maps. The view for this map is left lateral at a 45° elevation, looking down on parietal skull. The source lies approximately halfway between the peak-positive and -negative activity. The three-dimensional location of the source within the head is calculated mathematically (see text).

B, Magnetic-field map of the somatosensory response recorded over the right (affected) side of the head in patient 1. The magnetic-field map and source activity are displaced anteriorly by the mass lesion. View is right lateral at a 45° elevation.

Fig. 5. Case 2.

A, Magnetic-field map of the somatosensory response recorded over the left (normal) side of the head in patient 2. View is approximately left lateral at a 60° elevation.

B, Magnetic-field map of the somatosensory response recorded over the right (affected) side of the head in patient 2. The map and source activity are displaced posteriorly by the mass lesion. View is approximately right lateral at a 46.9° elevation.

Intracranial masses may significantly displace the location of the sensorimotor cortex as illustrated in these cases. The clinical ability to detect the displacement is insufficient. In our first case, the sensorimotor activity was localized by MSI to be anterior to the mass and, in the second case, posterior to the mass. Ideally preoperative, noninvasive, or intraoperative localization should be performed to accurately determine the location of essential cortex prior to surgical resection (1).

The biomagnetic fields detected by MEG are extremely small compared to the earth's magnetic field, and background magnetic noise that may be as much as 10,000 times the neuronal magnetic field being monitored. These neuronal magnetic fields are extremely small when compared to the values in Tesla (10,000 gauss) and gauss typical of MR. The neuronal activity is generally measured in picotesla (1 pT = 10^{-12} T) and femtotesla (1 fT = 10^{-15} T) (7). Detection of these small magnetic fields requires both a magnetically shielded room and the use of sophisticated instrumentation involving superconducting technology. A biomagnetometer is the MEG instrument used and consists of niobium detection coils emersed in liquid helium contained within a Dewar flask. A superconducting quantum interference device (SQUID) acts as a magnetic-field-to-voltage convertor for the detection coils of the biomagnetometer which are positioned close to the scalp surface (8). The weak neuronal magnetic fields are monitored by the neuromagnetometer and then displayed by plotting magnetic-field lines or contour maps (Figs. 4 and 5). The contour map is an image of the magnetic-field amplitudes that emanate from the neuronal source located in a sulcus or fissure. The magnetic fields that emerge from the brain are positive on one side of the neuronal source and reenter the brain as a negative field on the opposite side of the source. The x, y, and z coordinates of the source are identified in reference to three points designated prior to acquisition of the MEG data. Once these three points have been identified on the corresponding MR images, it is possible to calculate the x, y, and z coordinates from a designated center of the head and superimpose the MEG location on the MR images (Figs.

1–3). The resulting "montage of information" has been termed a magnetic source image (MSI) (8).

Noninvasive preoperative cortical localization influenced the clinical management of the two patients presented. In both of these cases, the neurosurgeon altered his planned surgical approach based on the MSI results. The remarkably rapid recovery to a normal neurologic status in case 2 can be related to the surgeon's ability to avoid the sensorimotor cortex. In addition to previous uses of this technology in the evaluation of seizure disorders, applications may also include the evaluation of vascular malformations, drug efficacy, psychiatric disorders, and dementia (7, 8). MSI is a challenging new technology that may be drastically altered by the availability of more sophisticated MEG and MR systems. Thirty-seven-channel MEG equipment is currently available, and this technology will markedly reduce the acquisition times for MEG data, as well as improve the accuracy of the localization. Coupled with the remarkable advances in MR, MSI is rapidly evolving as a potential clinical modality.

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