Primary Thumb Sensory Cortex Located at the Lateral Shoulder of the Inverted Omega-shape on the Axial Images of the Central Sulcus

Toshihiro KUMABE, Nobukazu NAKASATO, Takashi INOUE, and Takashi YOSHIMOTO

Department of Neurosurgery, Tohoku University School of Medicine, Sendai

Abstract

Useful landmarks on magnetic resonance (MR) images were identified for preoperative prediction of the relationship of a tumor to the primary sensory cortex of the thumb. Functional MR (fMR) imaging and magnetoencephalography were used to retrospectively localize the hand-digit sensorimotor area in four patients who underwent tumor resection around the central sulcus with intraoperative neurophysiological mapping. fMR imaging revealed the hand-digit motor cortex in the so-called “precentral knob” inside the characteristic inverted-omega on axial MR images. Equivalent current dipoles of the N20m response in somatosensory evoked fields (SEFs) of the thumb, median nerve, and ulnar nerve stimuli were localized at the lateral portion of the inverted omega-shape from the lateral to medial directions. The SEF-based thumb sensory cortex was verified by intraoperative functional mapping with a neuronavigation system. The hand-digit somatosensory cortices were localized at the lateral shoulder of the inverted-omega, in the lateral anterior inferior position to the hand-digit motor cortices in the precentral knob. Axial MR imaging can provide useful preoperative planning information for the surgical treatment of tumors within or adjacent to the motor-somatosensory cortex.

Key words: brain mapping, central sulcus, functional magnetic resonance imaging, magnetoencephalography, motor cortex, sensory cortex

Introduction

Localization of the central sulcus is essential in neurosurgical planning for the treatment of lesions adjacent to the primary sensorimotor cortices. Localization of the somatotopic arrangement is also important. The anatomic organization in the primary motor cortex of the orofacial muscles is different from the limb muscles, such as the bilateral cortical representation of facial muscle movements. Since the thumb sensorimotor cortex is located in the boundary between the orofacial and limb sensorimotor cortex, localization of the thumb sensory cortex and hand-digit motor cortex is necessary to avoid permanent sensorimotor deficits. Intrinsic tumors involving the nondominant face motor cortex can be safely removed.15

Intraoperative cortical mapping techniques are the gold standard of brain mapping, but a preoperative noninvasive method for obtaining the same information is highly desirable to eliminate the added time and inconvenience associated with intraoperative mapping, and aid in presurgical planning. Magnetic resonance (MR) and positron emission tomography (PET) imaging studies have demonstrated that the hand functional area in the sensorimotor cortex is easily identified as a characteristic sigmoidal shape on axial MR images.19 The central sulcus also has a characteristic curved shape resembling the letter omega on axial MR images at the somatosensory hand area identified by functional MR (fMR) imaging.17 The neural elements involved in motor hand function are located in a characteristic “precentral knob” which is shaped like an omega or epsilon in the axial plane and like a hook in the sagittal plane.23 However, the anatomic relationship between the hand-digit motor and sensory cortices remains unclear.

Magnetoencephalography (MEG), the measurement of weak magnetic fields generated by intracerebral electric currents, is applicable to func-
tional brain mapping. MEG can achieve accurate source localization because it is little affected by the inhomogeneous conductivity of the head. The characteristic advantage of MEG is high spatial and temporal resolution. Recently, we demonstrated the fine correlation between anatomy and function in the human digit cortex based on detection of the somatosensory evoked magnetic fields (SEFs) using our MR imaging-linked whole head MEG system. This study indicated that the human digit sensory cortex is located within one convexity of the post-central gyrus. The positions of the individual digit dipoles are arranged from lateral anterior inferior to medial posterior superior in the order of thumb, index finger, middle finger, ring finger, and little finger.

The present study correlated functional data about the hand-digit sensorimotor cortex derived from fMR imaging, MEG, and intraoperatively derived brain mapping with MR imaging in patients undergoing tumor resection within the primary sensorimotor area to identify useful landmarks on MR images that could be used preoperatively to predict the relationship of a tumor to the primary sensory cortex of the thumb.

Materials and Methods

I. Clinical materials

This study included three males with astrocytoma and one male with metastatic brain tumor in the primary motor-somatosensory cortex. The patients were aged from 26–62 (mean 36) years and presented with seizures and/or sensorimotor deficits. The clinical features are outlined in Table 1. Informed consent was obtained from all patients.

II. Anatomical MR imaging

All patients underwent three-dimensional (3-D) MR imaging with three fiduciary markers on the nasion and preauricular points. These fiduciary points were identified on the reconstructed 3-D image of the head and the MR imaging coordinate system was transformed to the MEG coordinate system. The MR imaging head shape data was used to determine the best fit single sphere for each subject’s head for source modeling.

III. SEFs

SEFs were recorded while the subjects were sitting comfortably in a magnetically shielded room with the head supported against the helmet-shaped sensor array of the magnetometer. The thumb, median nerve at wrist, and ulnar nerve at wrist were stimulated bilaterally, in different recording runs, with an electrical square-wave pulse of 0.3 msec duration at 2.7 Hz. Stimulus intensity varied from 3 to 10 mA in different subjects, and was adjusted to produce a muscle twitch without causing discomfort.

SEFs were recorded with a helmet-shaped Neuromag-122™ magnetometer array (Neuromag, Helsinki, Finland), which has 122 planar first-order SQUID gradiometers at 61 measurement sites. Each sensor unit contains a pair of gradiometers to measure two orthogonal tangential derivatives of the magnetic field component normal to the helmet surface at the sensor location. The planar gradiometers are most sensitive just above the local source area, where the field gradient is maximum. The exact location of the head with respect to the sensors was established by measuring magnetic signals produced by currents in three head position indicator coils, placed at known sites on the scalp. The locations of the coils with respect to the anatomical landmarks of the head were determined with a 3-D digitizer to allow alignment of the MEG and MR imaging coordinate system. T1-weighted MR images of all subjects were acquired with a 1.5 T MR imaging system (Sigma Horizon™; GE-Yokogawa, Tokyo). Further technical details of the MEG method and MEG/MR imaging integration are available elsewhere.

The SEF signals were bandpass filtered (0.03–300 Hz).

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age</th>
<th>Sex</th>
<th>Diagnosis</th>
<th>Presenting symptoms</th>
<th>Navigation system</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26</td>
<td>M</td>
<td>Lt face-tongue sensory area anaplastic astrocytoma</td>
<td>Generalized seizure</td>
<td>Frameless stereotaxy</td>
</tr>
<tr>
<td>2</td>
<td>62</td>
<td>M</td>
<td>Lt finger motor area metastatic tumor</td>
<td>Rt upper arm-finger motor weakness</td>
<td>Frameless stereotaxy</td>
</tr>
<tr>
<td>3</td>
<td>26</td>
<td>M</td>
<td>Rt face motor fibrillary astrocytoma</td>
<td>Facial seizure followed by secondary generalization</td>
<td>Ultrasound</td>
</tr>
<tr>
<td>4</td>
<td>31</td>
<td>M</td>
<td>Lt frontal operculum anaplastic astrocytoma</td>
<td>Dysarthria, motor aphasia</td>
<td>Ultrasound</td>
</tr>
</tbody>
</table>

Neurol Med Chir (Tokyo) 40, August, 2000
Hz), digitized at 1.25 kHz, and about 200 single responses were averaged on-line. The analysis period of 350 msec included a prestimulus baseline of 20 msec. The source location and orientation of the first cortical component (N20m) were estimated using a single current dipole model and the best fit sphere for each subject's head, then superimposed on the MR images.

IV. fMR imaging

fMR imaging was performed with a commercial 1.5 T whole body scanner (General Electric Medical Systems, Milwaukie, Wis., U.S.A.) and the standard head coil. The patient's head was fixed with Velcro tape, an airmat, and a neck collar. Seven oblique axial slices, parallel to the bicommissural line, were obtained as anatomical reference images using a T1-weighted inversion recovery echo planar imaging (EPI) sequence: repetition time (TR) 2000 msec, inversion time 800 msec, echo time (TE) 20 msec, 24 x 24 cm field of view (FOV), 128 x 128 matrix, and a slice thickness of 10 mm; or a T1-weighted EPI sequence: TR 3000 msec, TE 100 msec, 24 x 24 cm FOV, 256 x 192 matrix, and a slice thickness of 10 mm. fMR imaging was performed on the same slices using a gradient echo type EPI sequence: TR 3000 msec, TE 60 msec, flip angle 90 degrees, 24 x 24 cm FOV, 64 x 64 matrix, and a slice thickness of 10 mm. fMR imaging consisted of six 30-second epochs (each corresponding to 10 images in each of the 7 slices) alternating between rest and activation so that 420 images were obtained per imaging run. The specific test was repetitive opening and closing of the hand at about one cycle per second. The tests were performed independently on each side and repeated twice. The series of images was viewed in cine mode to reject runs with head movement. Functional images were analyzed with a workstation (SPARC station 20; Sun Microsystems, Mountain View, Calif., U.S.A.) connected to the MR imaging system using image analysis software (FuncTool™; GE Medical Systems, Buc, France). The time intensity curve of each pixel was plotted and compared with a reference function by a cross correlation program. The reference function was a square wave with a period of 30 seconds. The activation map was generated using pixels with a correlation coefficient of >0.6. [22]

V. Intraoperative cortical stimulation

All four patients underwent intraoperative functional brain mapping under awake craniotomy. The technique of electrical stimulation mapping was described previously.[9] Briefly, a bipolar electrode with 5 mm spacing between the tips was applied to the brain surface for 2 to 3 seconds. A biphasic, square-wave pulse (60 Hz, 1 msec duration) was delivered from a constant generator to elicit the desired sensorimotor responses. The current varied between 2 and 12 mA. Numbered labels were placed on the cortical surface corresponding to specific motor movement and sensory evoked potentials, and photographs taken prior to and following resection and stored with the schematic drawing of the patient's brain map.

VI. Frameless stereotactic navigation device

A frameless stereotactic navigation device (ISG Viewing Wand; ISG Technologies, Mississaugua, Ontario, Canada) was used in Cases 1 and 2. These two patients were scanned with external skin fiducial markers fixed to the skin outside the skin incision on the day before the operation, which were then used as reference points during registration. Once the functional mapping was completed, the tip of the wand was positioned on these fiducial markers, which could be easily recognized on the 3-D reconstruction. The cursor on the computer screen was positioned on the same point on the 3-D image and the points correlated. The accuracy of correlation was within 3 mm. The scalp landmarks were selected to confirm the accuracy of registration. The specific motor movement and sensory evoked cortices were recorded by the ISG Viewing Wand. Postoperatively, these functional cortices were compared with the results of fMR imaging and MEG.

Results

fMR imaging revealed that the hand-digit motor area was located at the posterior bank of the precentral knob, which was shaped like an inverted omega on the axial MR images. Opening and closing of the hand, as used in the present fMR imaging study, stimulates both the primary motor and sensory cortices, and the association cortex including the supplementary motor area. MEG detected each SEF with high accuracy. The positions of the N20m dipoles for the thumb, median nerve, and ulnar nerve were localized at the lateral portion of the inverted omega-shape from the lateral anterior inferior to medial posterior superior directions. The thumb N20m dipole was oriented anteriorly whereas the median and ulnar nerve N20m dipoles were more medially and superiorly oriented. All N20m dipoles were almost perpendicular to the central sulcus (Figs. 1-5). Intraoperative neurophysiological mapping revealed the thumb sensory area was located at the characteristic bend of the postcentral gyrus. This
area recorded by the neuronavigation system corresponded to the thumb SEF on MEG (Figs. 8 and 7).

**Illustrative Case**

**Case 1:** A 26-year-old right-handed male developed generalized seizure activity 3 months before admission. Neurological examination showed no abnormalities. T2-weighted MR imaging revealed a high intensity lesion in the lateral posterior portion of the left parietal lobe (Fig. 1). The tumor had invaded the lateral portion of the gyrus posterior to the inverted omega-shaped sulcus. There was no contrast enhancement with gadolinium. MR imaging-linked MEG revealed that the tumor was located within the primary sensory cortex. The N20m SEF dipoles of the thumb, median nerve, and ulnar nerve were localized on the posterior bank of the omega-shaped sulcus. The N20m dipole of the ulnar nerve was localized at a medial posterior superior position to the N20m dipole of the median nerve. The N20m dipole for the thumb was localized at the lateral portion of the gyrus posterior to the inverted omega-shaped sulcus which was invaded by the tumor. fMR imaging revealed the hand-digit motor area was located at the posterior bank of the precentral knob.

A frontoparietal craniotomy was performed under awake craniotomy. The thumb sensory cortex was located at the characteristic bend of the postcentral gyrus, and the hand-digit motor cortex at the medial
antior superior precentral gyrus. The results of intraoperative brain mapping by the ISG Viewing Wand revealed the thumb sensory cortex in the same location as shown by the thumb SEF and the hand-digit motor cortex in the same location as shown by fMR imaging (Fig. 6). The entire lesion was resected. Histological examination indicated an anaplastic astrocytoma.

Postoperatively, the patient complained of sensory loss in the right side of the face and right thumb. All sensory disturbance disappeared within a week except for the slight sensory disturbance of the right thumb. Postoperative MR imaging revealed that the tumor was resected completely. The patient received postoperative radiochemotherapy.

Discussion

The high spatial resolution of the MR imaging-linked whole head MEG system can reveal the relationship of a tumor to the hand-digit sensory cortex, as demonstrated in this study. The thumb sensory cortex was accurately localized in all of our patients to the posterior bank of the lateral shoulder of the inverted omega-shaped sulcus on the axial MR images. The positions of each SEF for the thumb, median nerve, and ulnar nerve were localized from the lateral anterior inferior to medial posterior superior directions at the lateral portion of the inverted omega-shape.

The central sulcus can be identified by anatomical
Fig. 3 Case 3. Preoperative T2-weighted magnetic resonance (MR) image (upper left), postoperative functional MR (fMR) image activated by opening and closing of the left hand (upper center), intraoperative photograph with functional brain mapping (upper right), and magnetoecephalograms (lower row). Highest activation of fMR imaging was located at the posterior bank of the precentral knob. The resection cavity was just beside this knob. Arrows indicate the central sulcus. The motor and sensory cortex areas are as follows: 1, tongue sensory; 2, thumb sensory; 3, little finger sensory; 4, hand-digit motor; 5, tongue motor. The gray, black, and white circles indicate the estimated N20m dipoles of the somatosensory evoked magnetic fields caused by stimuli of the thumb, the median nerve, and the ulnar nerve, respectively. The bars indicate the orientation of the dipole.

MR imaging. Multiplanar MR images can identify the central sulcus as a mirror-image pair of distinctly transverse sulci on the most rostral vertex T2-weighted axial MR images. The motor cortex can also be identified as the gyri directly anterior to the marginal sulcus, which is the terminal continuation of the cingulate sulcus on sagittal or slightly parasagittal midline sections. The accuracy of these methods was verified by comparison with intraoperative brain mapping. Another method of identification of gyri by recognition of the medullary pattern is practical at the level of the centrum semiovale. The central sulcus at that level has the inverted omega-shaped pattern.

The somatotopic arrangement of the sensorimotor area, 'homunculus,' has been revealed by the dipole tracing method using short latency somatosensory evoked potentials, PET, fMR imaging, and MEG. fMR imaging was used to detect the fine functional and anatomical relationship of the hand-digit motor area. The hand-digit motor area has a knob-like structure that is shaped like an omega or epsilon on axial MR images. This precentral knob on the cortical surface corresponds precisely to the characteristic middle knee of the central sulcus. This is a useful method to identify the hand-digit motor area. However, localization of the hand-digit 'sensory' area was not discussed.

We previously reported the usefulness of the MR imaging-linked whole head MEG system for non-in-
Fig. 4 Case 4. Preoperative T₁-weighted magnetic resonance (MR) image with gadolinium (upper left), postoperative functional MR (fMR) image activated by opening and closing of the right hand (upper center), intraoperative photograph with functional brain mapping (upper right), and magnetoencephalograms (lower row). Highest activation of fMR imaging was located at the posterior bank of the precentral knob. Arrows indicate the central sulcus. The motor and sensory cortex areas are as follows: 1, tongue sensory; 2, face sensory; 3, thumb sensory; 4, face motor; 5, tongue motor. The gray, black, and white circles indicate the estimated N20m dipoles of the somatosensory evoked magnetic fields caused by stimuli of the thumb, the median nerve, and the ulnar nerve, respectively. The bars indicate the orientation of the dipole.

Intrusive functional mapping of the central sulcus and digit sensory cortex.¹⁰,¹⁵,³⁶ Linkage to 3-D MR imaging and the use of the best fit sphere for individual patient head shape results in a more accurate estimation of the source position. Mapping of the signal source positions onto the MR images enables direct comparison of the results of functional localization with the corresponding anatomy. Using fMR imaging, the hand-digit motor area was located at the precentral knob, as previously reported.²⁹ The combination of fMR imaging and MEG could thus reveal the precise somatotopy of the primary sensorimotor area. This study found a good correlation between the preoperative estimates by MEG and fMR imaging and the relationship to the lesion and those found by intraoperative mapping. The method of identification of the thumb sensory cortex and the hand-digit motor cortex on the basis of the characteristic inverted omega-shaped pattern of the sulcus was extremely useful. We have since used this retrospective information to plan surgical approaches for cortical and subcortical lesions around the central sulcus.

Intraoperative direct cortical stimulation or recording is arguably the gold standard for the localization of the motor and somatosensory cortex in patients undergoing resection of lesions near or in the eloquent brain. However, preoperative noninvasive functional brain mapping techniques such as MEG, fMR imaging, and PET allow the planning of the surgical procedure, and combination with intraoperative anatomical mapping techniques such as frameless stereotaxy can achieve the optimum preservation of the sensorimotor function.
Fig. 5 Schematic drawing of the inverted omega-shape as demonstrated on axial magnetic resonance images of the central sulcus. The gray, black, and white circles indicate the estimated N20m dipoles of the somatosensory evoked magnetic fields caused by stimuli of the thumb, the median nerve, and the ulnar nerve, respectively. The bars indicate the orientation of the dipole. A: Case 1, B: Case 2, C: Case 3, D: Case 4.

Fig. 6 Case 1. Recording of the sites (cross-hairs) of the thumb sensory cortex (left) and the hand-digit motor cortex (right) using the neuronavigation system.

Fig. 7 Case 2. Recording of the sites (cross-hairs) of the thumb sensory cortex using the neuronavigation system.

in patients with mass lesions in the primary sensorimotor cortex. In the future, the integration of noninvasive functional mapping data and stereotactic data bases will undoubtedly improve. Further studies will elucidate the correlation between the brain function and the structural details.

In conclusion, this new method can identify the thumb sensory area on axial MR images of the brain on the basis of the pattern of the sulcus. The thumb sensory cortex is located at the lateral shoulder of the inverted omega-shape on axial MR images of the central sulcus, facing the hand-digit motor cortex located in the precentral knob. Such simplified schematic concepts of sulcal patterns will help functional brain mapping and presurgical planning.

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References


Address reprint requests to: T. Kumabe, M.D., Department of Neurosurgery, Tohoku University School of Medicine, 1–1 Seiryo–machi, Aoba–ku, Sendai 980–8574, Japan.
Commentary

The relationship between structure and function in clinical neuroscience has been the subject of considerable interest and discussion for over a century. As neuroimaging and neurophysiological tools have evolved that enable exploration of this relationship, we have learned much and the pendulum has periodically swung between high correlation and worrisome variability. Functional MRI, MEG, intraoperative corticography, cortical stimulation and reliable spatial coregistration now have provided a superb opportunity to resolve clinically vital issues for surgical planning and resection.

Kumabe and colleagues in this report further our understanding of functional localization. They have documented the functional organization for a limited but important cortical area, demonstrated the ability of MEG to provide such information, and shown a highly correlated consistency with respect to the anatomy. That they were able to make reliable recordings and correlations in the setting of underlying tumors that distorted the anatomy reflects the refinement of their technique but also reconfirms the increasing power of such methodology in the practical, clinical setting. Lehéricy and colleagues recently achieved similarly encouraging results with fMRI in their investigation of this same region. It is likely that a more limited set of preoperative studies will eventually suffice for clinical purposes, but to what degree more highly resolved structural imaging may ultimately provide reliable functional localization is at present unknown. In the meantime, studies such as this one continue the important process of validation of both newer and well-established methods.

Reference


David W. Roberts, M.D.
Section of Neurosurgery
Dartmouth-Hitchcock Medical Center
Lebanon, N.H., U.S.A.

Kumabe et al. investigated the location of the primary thumb sensory cortex, and compared the result of functional MR imaging with hand grasping task, equivalent current dipoles of N20m response in somatosensory evoked fields (SEFs) of the thumb, median nerve, and ulnar nerve detected by MEG, and sensorimotor cortex of hand and face area by intraoperative functional mapping under local anesthesia. They clearly demonstrated that the thumb sensory cortex is located at the lateral shoulder of the inverted omega-shape on axial MR imaging of the central sulcus. The accuracy and usefulness of preoperative examinations, such as functional MR imaging and SEFs on MEG, for tumor surgery within and around the sensorimotor cortex is described briefly in this study. It is very interesting to know which degree the sensorimotor cortex of the hand-digit can move, and in which direction it can move due to the effect of compression by a tumor and perifocal edema. It is desirable to recognize not only the location but also the extent of the functional area of the hand-digit sensorimotor cortex preoperatively. Further studies are necessary to assess the precise relationship between the functional area and anatomical structure near the eloquent cortex.

Toshisuke Sakaki, M.D.
Department of Neurosurgery
Nara Medical University
Kashihara, Nara, Japan

Exact identification of the rolandic area on MR images or on the cortical surface during surgery is very important and of great concern for every neurosurgeon. Rumeau et al. (1994) found that the superior genu of the central sulcus corresponds to hand function in the sensorimotor cortex. This part of the central sulcus is well detected as a characteristic sigmoidal form on axial planes of MR imaging. This work was performed based on comparative studies of MR imaging and PET. Yousry et al. (1997) further refined Rumeau’s study, using functional MR (fMR) imaging. According to their report, the area of motor hand function is located in a characteristic ‘precentral knob’ in the upper part of the precentral gyrus. Once accustomed to this shape, it is quite easy to detect the ‘precentral knob’ on the axial plane of MR imaging. The most important point is that this characteristic shape of the hand motor area is preserved even under pathological conditions. Therefore, this can be a very instrumental landmark to plan the surgical strategy in patients with tumors or vascular lesions in the peri-rolandic areas. Kumabe et al. have added very elegant scientific data to Yousry’s findings. They have effectively combined the sophisticated techniques of MR imaging, fMR imaging, MEG and somatosensory evoked fields. All four patients harbored tumors in the peri-rolandic areas. Even under these pathological conditions, the hand-digit somatosensory cortices
were localized at the lateral shoulder of the precentral knob. The new knowledge offered by this paper might not be so extensive, but I would like to applaud their meticulous and sophisticated clinical research methods.

Hiroyuki SHIMIZU, M.D.
Department of Neurosurgery
Tokyo Metropolitan Neurological Hospital
Fuchu, Tokyo, Japan

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