

Motor cortex localization using functional MRI and transcranial magnetic stimulation

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Article abstract—*Objective:* Congenital brain lesions producing focal seizures may be accompanied by reorganization of the areas responsible for motor and sensory functions within the brain due to a phenomenon that has been termed “neuronal plasticity.” This can be studied using functional MRI (fMRI) and transcranial magnetic stimulation (TMS). Using either method, the motor cortex can be localized noninvasively, but to date there have been few studies correlating the level of agreement between the two techniques. *Methods:* We used fMRI and TMS to localize the motor cortex in a young woman with intractable focal seizures, congenital left arm weakness, and a dysplastic right hemisphere on MRI. *Results:* There was excellent agreement in the localization of motor representation for each hand. Both were predominantly located in the left hemisphere. fMRI also showed an area of posterior activation in the right hemisphere, but there was no evidence of descending corticospinal projections from this site using TMS, direct cortical stimulation, and Wada testing. *Conclusions:* Functional MRI (fMRI) and transcranial magnetic stimulation (TMS) were successfully used to localize cortical motor function before epilepsy surgery. Each technique demonstrated migration of motor function for the left hand to the left motor cortex. After resection of the dysplastic right precentral gyrus there was no permanent increase in weakness or disability. The two techniques are complementary; fMRI indicates all cortical areas activated by the motor task, whereas TMS identifies only those areas giving rise to corticospinal projections. **Key words:** fMRI—Transcranial magnetic stimulation—Epilepsy—Neuronal plasticity.

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Successful surgery for focal epilepsy requires accurate localization of the seizure focus. Resection of this area would preferably not lead to any increase in neurologic disability but produce a reduction in seizure frequency.

In the past it was not possible to evaluate the functional effects of cortical resection of epileptogenic areas noninvasively. Consequently surgery involving eloquent cortical areas was preferably performed with the patient awake so that the patient could report the effects of direct electrical stimulation of the area to be resected,¹ or invasive preoperative studies using intracranial electrodes had to be performed.

Recently two techniques have been developed, transcranial magnetic stimulation (TMS) and functional MRI (fMRI), which can be used to localize the motor cortex noninvasively. The methodology of the two techniques is different. fMRI registers changes in oxyhemoglobin levels secondary to focal changes in cortical activity,² whereas TMS directly stimulates corticospinal neurons or interneurons synapsing on corticospinal neurons within the motor cortex.^{3–6} Focal mapping of motor cortex location using TMS can be accomplished using a figure-eight coil. This has been performed in a large number of normal subjects as well as in patients with a number of pathologic

conditions with reproducible results.^{7–9} There have been some concerns that areas of activity demonstrated by fMRI may be in draining veins at some distance from the areas of increased neuronal activity,¹⁰ but a recent study demonstrated a close spatial correlation between fMRI and TMS in motor cortex localization.¹¹ This is the first occasion, to our knowledge, where the results of fMRI and TMS have been used in the assessment of cerebral localization before surgical resection of epileptogenic cortex.

Case report. A 20-year-old woman was born after a forceps delivery. She began having subtle twitches from birth and was diagnosed as having infantile spasms at 3 weeks. The seizures initially responded to treatment with nitrazepam and prednisolone, but she had never been seizure free for any extended period. At the time of evaluation for surgery she was having frequent bursts of focal myoclonus affecting the left arm and leg. These varied from long periods of minor shaking to overt major jerks and could culminate in a secondarily generalized tonic-clonic seizure. She had up to four tonic-clonic seizures per week and daily minor seizures before surgery. She had been on multiple combinations of anticonvulsants throughout her life. At the time of these studies she was taking vigabatrin 1 g bid, carbamazepine 1.1 g/d, phenytoin 0.2 g/d, and clonazepam 2.5 mg/d. A left hemiparesis was evident in the first year of

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Figure 1. Preoperative MRI demonstrating a focal area of cortical dysplasia in the region of the right central sulcus.

life. She had little fine motor control in her left hand but did have some grasp and sufficient function in the left arm and hand to make the limb useful in everyday life. She was able to walk without aids, but there was reduced sensation in the left arm and leg. Close observation revealed that moving the fingers of her left hand caused subtle "mirror movements" in her right hand. Her MRI demonstrated dysplasia in the region of the right central sulcus (figure 1).

An intracranial electrode plate was inserted over the right hemisphere, encompassing the dysplastic area and the pre- and postcentral gyri (figure 2). Several seizures were recorded demonstrating seizure onset from this region. With the patient awake, electrical stimulation of the cortex through each electrode site on the plate did not elicit any clonic motor responses on the left side or any sensory symptoms. On a number of occasions during stimulation, auras occurred without clear EEG change, but stimulation at the superior part of the second chain of electrodes reproducibly led to intensification of aura symptoms and clear-cut after discharges. A Wada test was performed using an injection of sodium amobarbital into the right carotid artery. This produced no increase in the left-sided weakness or sensory loss but decreased the degree of spasticity present in her left arm.

Having established that the dysplastic area in the right hemisphere on MRI was the epileptic focus, could this area be safely resected without increasing her motor and sensory deficit? We evaluated this using a number of different techniques to determine whether the abnormal area of cortex was involved in motor or sensory function.

Methods. *Somatosensory evoked potentials.* Somatosensory evoked potentials (SEPs) were obtained by stimu-

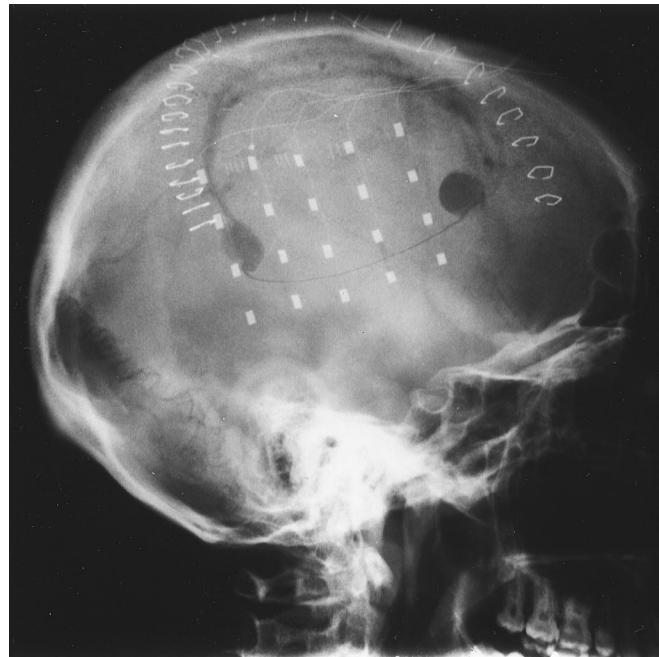


Figure 2. Skull radiograph illustrating the intracranial electrode plate over the right hemisphere.

lating the median nerve at the wrist while the patient lay on a reclining couch. No sedative drugs were used. Room temperature was kept constant by central air conditioning. The recording electrodes were silver-silver chloride disks adhered with collodion and soaked with EKG gel to maintain impedance below 5 kilohm. The response was recorded over the contralateral scalp by electrodes situated in postrolandic positions 3 cm behind and 7 cm lateral to the vertex (Cz; International 10-20 System). Additional active electrodes were situated at Erb's point ipsilateral to median nerve stimulation and over the C6 spinous process. Reference electrodes were located on linked earlobes. The stimulus used was a 0.1-msec square wave pulse, and each side was tested independently. The distance between the centers of the stimulating electrodes was 2 cm with the cathode at the proximal end. Stimulus intensity was adjusted to produce a just-visible thumb twitch, and the rate was three per second. The input was fed to a four-channel Sapphire Premiere EMG (Medelec; Old Woking, Surrey, UK). The frequency bandpass was 20–3,000 Hz with an analysis time of 100 msec. The response to 512 stimuli was averaged, and at least two averages were obtained to ensure response reproducibility. Using the same technique, an attempt was made to record SEPs from each electrode on the intracranial plate using Fz as reference during left median nerve stimulation at the wrist.

MEP mapping. After removal of the intracranial electrode, TMS was performed using a flat 50-mm figure-eight coil and a MAGSTIM 200 stimulator (Dyfed, Wales, UK). The subject sat in a comfortable chair, and a transparent tightly fitting skullcap was fixed with reference to four landmarks (inion, nasion, and the top of each ear). The vertex was measured, and the approximate site of the hand area of the motor cortex (7 cm from the vertex along a line drawn from the vertex to tragus) was identified. Using this point as the center, a 1 × 1 cm grid covering 6 cm² was drawn on each side with the cap in position. The

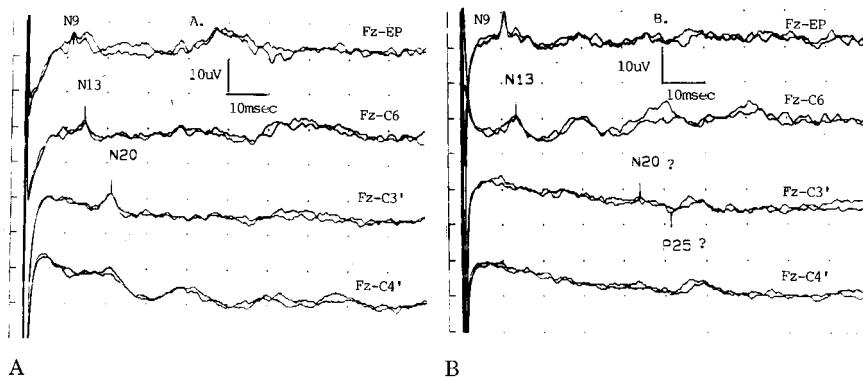


Figure 3. Somatosensory evoked potentials obtained by right and left median nerve stimulation. (A) Right median nerve stimulation at Erb's point, C6, C3', and C4' using a linked earlobe reference. (B) Left median nerve stimulation at Erb's point, C6, C3', and C4' using a linked earlobe reference.

junction of the coil loops was held tangential to the scalp with the loops of the coil equidistant from the skin. The coil handle directed posteriorly. Motor evoked potentials (MEPs) were recorded from the first dorsal interosseus (FDI) muscles at rest bilaterally using surface electrodes using a Medelec Sapphire Premiere EMG filtered with a high frequency of 5 kHz and a low frequency of 20 Hz. Sensitivity was set initially at 200 μ V per division and sweep speed at 50 msec. Stimulus intensity was 100%, and five stimuli were given at each site. A map of motor cortical output was produced by measuring the mean peak-to-peak amplitude of MEPs evoked at each site on the grid.

fMRI. Acquisition. fMRI data were obtained with a 1.5-T Siemens (Erlangen, Germany) MRI system using a quadrature head coil as both transmitter and receiver. Field homogeneity was adjusted with global shimming, with typical line widths for the global shimming being approximately 20 Hz. Whole-brain anatomy was examined using a T1-weighted MPRAGE 3-D sequence. From this, slice positions were determined, and planes were selected in standard axial and in an angled plane to cover the central sulcus from the sylvian fissure to the interhemispheric fissure.¹² This covers the primary motor cortex (PMC) and sensory cortex for the activation studies in a complete manner both for potential bilateral activation and displaced localization within the hemisphere. For subsequent anatomic co-registration, T1-weighted images were acquired in these axial and tilted axial planes using the same slice selection parameters as for the blood oxygen level dependent-weighted imaging. During the activation task the selected planes were imaged using a fast low-angle shot (FLASH)¹² sequence (repetition time/echo time 91 msec/60 msec, flip angle 40°, bandwidth 19 Hz, matrix size 64×128 , 1.95 \times 1.95 mm in-plane pixel size, 4-mm slice thickness) with the same field of view and section thickness as in the corresponding anatomic images. The FLASH images were interpolated and displayed as a 128×128 matrix.

Motor task. The subject was fitted with a molded thermoplastic head restraint to minimize head motion. Bilateral forearm, hand, and finger support was provided by molded plastic splints to isolate finger movement. The motor task consisted of repetitive index finger movements. The rate of movement was trained to 1-2 Hz with a metronome before scanning. The subject was able to perform this task with both the left and right hand. On careful examination, barely perceptible mirror movements of the right hand occurred with left hand and finger movement. Force of movement was not controlled. The study used a block

design with alternation of five images of rest and five images of hand movement motor task repeated for five cycles. Images were obtained over 7 seconds, with 1.5 seconds for eddy current stabilization and 1 second for attainment of steady state magnetization before acquisition.

Image analysis. Images were analyzed using in-house software with the Interactive Data Language programming language (Research Systems, Inc., Boulder, CO). This used an automatic iterative technique, which began with the entire image. At each pass it excluded pixels at less than 30% of the mean of the currently included pixels. A mild gaussian smooth (full width half-maximum = 3 mm) was applied to each image to ensure the noise characteristics or the data were approximately gaussian. A statistical parametric map was then obtained by performing a *t*-test at each pixel location to look for differences between the task and rest states. The first image of each task was excluded to allow the brain to reach hemodynamic equilibrium. Registration of these activation images with the anatomy was achieved by co-registering the identically oriented T1-weighted images with the activation maps.

Results. *Somatosensory evoked potentials.* A normal scalp response was recorded from the left hemisphere after right median nerve stimulation. Left median nerve stimulation produced a markedly delayed N20 response, which was most apparent on the ipsilateral scalp recordings (figure 3). No SEPs could be recorded from the intracranial plate overlying the right cortex.

TMS. MEPs were only produced in the left or right hands by left-hemisphere stimulation using TMS. No MEPs in either hand could be evoked by right-hemisphere stimulation (figure 4). Motor cortical projections to each hand were found in the left hemisphere at slightly different but overlapping locations in the vicinity of the precentral gyrus. The scalp area from which MEPs could be obtained from the right FDI muscle was substantially larger than that for the left FDI muscle. At the site of maximum MEP amplitude for each hand, motor threshold was also calculated. The threshold intensity (minimum stimulus intensity needed to produce three MEPs from six trials) was 40% for the right FDI muscle and 80% for the left FDI muscle.

The right FDI muscle localization correlated with the anatomic PMC, and the left FDI muscle was located in an area overlapping that for the right, but its center was slightly more inferior. No responses to TMS could be obtained from the right hemisphere, and, as noted above, no motor responses were obtained after stimulation through

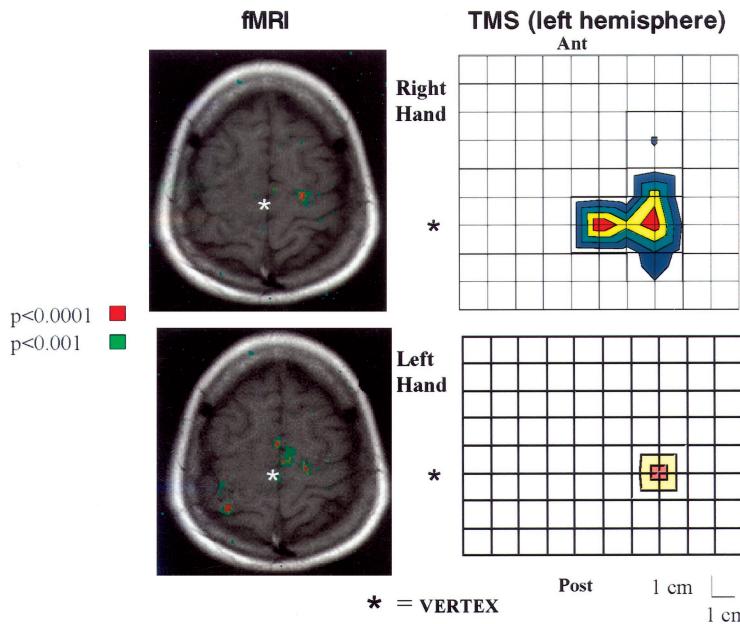


Figure 4. The functional MRI (fMRI) obtained during the motor task by right and left hands and motor evoked potential (MEP) mapping for the first dorsal interosseous muscle of each hand at rest using transcranial magnetic stimulation (TMS). The areas of significant activity on fMRI (uncorrected p values shown) and the regions of maximal MEP responses (amplitudes shown) for each hand in the central sulcus closely overlap using the two techniques. There is a second area of activity on fMRI for the left hand in the supplementary motor area bilaterally and in the contralateral somatosensory cortex. No MEPs could be recorded during right-hemisphere stimulation. Note that the scales for MEP amplitudes differ for the two hands.

each site of the intracerebral electrode plate. This was also the case when the area to be resected and its margins were directly stimulated intraoperatively.

fMRI. The movement task for each hand produced different areas of activation in the left hemisphere using fMRI. The right-hand task produced activation on fMRI in the left precentral gyrus in the area expected from the somatotopic maps of Woolsey and Penfield.¹ Left hand movement produced activation in the same area and slightly more inferiorly in the precentral gyrus. In addition there was strong activation in the supplementary motor

area (SMA) bilaterally on the medial surface of each hemisphere and in a small area in the normal anatomic region of the right somatosensory cortex (SSC). There was no activity in the dysplastic area of the right hemisphere where the epileptic focus was located (figure 4).

Comparison of fMRI with TMS and SEPs. There was excellent agreement between fMRI and TMS in the localization of motor representation within the left precentral gyrus. fMRI and TMS demonstrated evidence of overlapping foci of motor function for both right and left FDI muscles in this area. Comparing the two localization techniques, using the TMS scalp measurements translated to the fMRI image, there was a very close spatial correlation. fMRI activation was shown bilaterally in the SMA, an area not covered in the TMS mapping. The area in the right SSC activated on fMRI was an area covered by TMS mapping and the intracranial plate. It was also at the margins of the resection and was stimulated intraoperatively. Stimulation of the cortex by these three modalities did not produce motor responses nor were SEPs recorded from this area. The Wada test findings were also consistent with an absence of PMC in the right hemisphere.

Surgery and postoperative course. The patient underwent a resection of the dysplastic tissue after direct cortical stimulation of the area under local anesthetic did not produce any motor or sensory symptoms. The area resected abutted but did not include the area activated in the right hemisphere by the left hand motor task on fMRI (figure 5). The pathology of the resected specimen showed cortical dysplasia, ranging from mild to severe (focal cortical dysplasia). Postoperatively there was a mild increase in the degree of weakness of the left hand, which had the characteristics of a dyspraxia. This improved quickly, and left arm strength returned to its preoperative state within several weeks. She had four seizures in the first 4 months postoperatively but since then has had infrequent seizures with dramatic improvement in the quality of her life. Sensory auras persist. Her appearance has cosmetically improved, with marked reduction in the "spastic" posturing of her upper limb and improved gait.



Figure 5. Postoperative MRI demonstrating the resected area.

Discussion. This patient illustrates the extraordinary ability of the brain to remodel itself after abnormal development. Congruent localization of motor cortex using fMRI and TMS was demonstrated in both normal and remodeled corticomotor circuits. The results were used in presurgical evaluation of a patient with epilepsy and indicated that an epileptogenic area of cortical dysplasia could be safely removed with little risk of permanent postoperative motor deficit. This was subsequently confirmed by the postoperative course. The spatial agreement between fMRI and TMS in motor cortex localization for both hands was very close, given the limitations inherent in transferring surface scalp measurements to the MR image. Krings et al.,¹¹ using stereotaxic correlation of fMRI and TMS, showed that areas of maximum fMRI activation corresponded spatially to the areas of highest motor neuron density demonstrated electrophysiologically. In their study the TMS map tended to be larger than the fMRI map for corticomotor neurons in the PMC. This was also our finding and probably results from the spread of the electrical field induced by TMS at each point, rather than stimulation of motor neurons whose activation during the voluntary task did not produce an alteration in fMRI signal.¹¹ Larger motor cortex maps using TMS are produced using 100% stimulator output than those using stimulus intensity at motor threshold, illustrating this dependency of the map on the size of the induced electrical field.¹³

There is considerable evidence from animal experiments as well as human studies that recovery of function after CNS damage is in part dependent on the age at which it occurred.¹⁴ The earlier an experimental lesion is placed in the central motor pathways of a number of animals, including primates, the more complete the recovery. This is possibly because axonal sprouting after a lesion declines with age.^{15,16} Ipsilateral motor pathways in our patient were found using TMS and fMRI in the motor cortex (PMC) overlapping and slightly lower than those for the contralateral hand. The motor field for the ipsilateral hand extended into that normally occupied by the face. Similar findings have been reported after stroke,¹⁷ and recent evidence supports the notion that there are multiple and widespread representation areas of individual muscles in the PMC.^{17,18}

Ipsilateral motor pathway projections to hand muscles have been reported, particularly in patients with congenital neurologic deficits but also in apparently normal subjects and in patients after stroke.^{17,19,20} A number of mechanisms have been proposed, including lack of regression of normally transient fetal connections, enhanced development of normally occurring ipsilateral projections, abnormal ipsilateral branching of undamaged corticospinal axons, and aberrant ipsilateral projections.¹⁵ Collateral sprouting is the most common mechanism, and this in turn can give rise to mirror movements.^{15,21} These movements were subtly present in our patient.

In this patient, fMRI also showed bilateral in-

crease in SMA activity and an area of increased activity in the right SSC on left hand movement. This observation is very similar to the fMRI findings in normal volunteers during complex, self-paced motor tasks. In normal subjects, simple self-paced tasks produce fMRI activation only in the contralateral PMC, whereas complex, self-paced movements produce activation in the SMA, premotor cortex bilaterally, and the contralateral SSC.²² Activation of motor areas other than the primary sensorimotor cortex is a consistent finding following recovery after both congenital and acquired lesions of the PMC.²³⁻²⁵ The likelihood of SMA activation is also increased when patients have mirror movements. An increased role of the SMA has also been reported in primates after recovery from lesions of the PMC.²⁶ Increased activity in the SMA has been associated with the initiation, programming, selection, learning, and responsiveness to internal cueing of movements or selection of appropriate neuronal populations necessary to execute a movement.^{22,27} Imaging a complex motor task also produces activation in the SMA.²²

The area activated on fMRI in the right SSC is unlikely to represent migrated motor cortex. The failure of TMS or electrical stimulation either intraoperatively or via the intracranial plate to evoke motor responses from it indicates that it lacks direct corticomotoneuronal projections. This is also supported by the failure of the Wada test to produce left-sided weakness. This area and both SMAs in this patient are likely to be more involved in the planning rather than the execution of movement by the left hand.

Although there was no evidence of direct motor connections in the dysplastic area resected, the patient's focal seizures were mainly of the simple motor type affecting the left arm. It is tempting to speculate that cross-callosal connections were retained linking the right hemisphere dysplastic, epileptogenic area and the area in the left postcentral gyrus activated on fMRI by ipsilateral hand movement. Interference with these pathways by surgery might explain the transient left-sided weakness noted postoperatively.

SEPs demonstrated a very delayed response in the ipsilateral hemisphere after left median nerve stimulation and a normal response from the contralateral hemisphere after right median nerve stimulation. This indicates that there had also been reorganization of sensory pathways, both projecting to the left hemisphere in this subject. The development of a new ipsilateral projection of the somatosensory pathway has been reported to occur in patients with congenital dysplasia.¹⁵ It is thought to reflect brain damage and reorganization occurring before 20 to 24 weeks' gestation because the somatosensory pathway is complete after this time.²⁸

fMRI and TMS can both be used noninvasively and are free of side effects. They can be used repeatedly, and both show considerable promise as a means of studying alterations in cortical functional architec-

ture after a number of pathologies such as stroke. The two techniques are complimentary. fMRI will identify all areas of increased cortical activity during a motor task. TMS only produces responses from areas of direct, descending motor pathway projection.^{10,29-31} TMS can thus be used to study the likely role of areas activated by movement on fMRI.

fMRI and TMS should become more useful in the future to localize brain function noninvasively and thus reduce the risk of postoperative deficit in difficult cases. They also have considerable potential in the study of the phenomenon of neuronal plasticity and reorganization after congenital or acquired brain lesions.

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