Whole-hand sensorimotor area: cortical stimulation localization and correlation with functional magnetic resonance imaging

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Object. The pli de passage moyen (PPM) is an omega-shaped cortical landmark bulging into the central sulcus. There has been considerable interest in the PPM given that hand motor and sensory tasks have been found on functional magnetic resonance (fMR) imaging to activate the structure. Note, however, that the cortical function subserved by the PPM is not completely understood. Finger and thumb function are somatotopically organized over the central area and encompass a larger cortical surface than the anatomical PPM. Therefore, a sensory or motor hand area within the PPM would be redundant with the somatotopically organized digit function in the primary sensorimotor cortex. In this study the authors aimed to clarify the function subserved by the PPM and further evaluate hand area function in the primary sensorimotor cortex.

Methods. To further elucidate the function subserved by the PPM, patients underwent cortical stimulation in the region of the PPM as well as fMR imaging–demonstrated activation of the hand area. Two separate analytical methods were used to correlate hand area functional imaging with whole-hand sensory and motor responses induced by cortical stimulation.

Results. A relationship of the anatomical PPM with cortical stimulation responses as well as hand fMR imaging activation was observed.

Conclusions. A strong relationship was identified between the PPM, whole-hand sensory and motor stimulation responses, and fMR imaging hand activation. Whole-hand motor and whole-hand sensory cortical regions were identified in the primary sensorimotor cortex. It was localized to the PPM and exists in addition to the somatotopically organized finger and thumb sensory and motor areas. (DOI: 10.3171/JNS/2008/108/3/0491)

Key Words • cortical stimulation • functional magnetic resonance imaging • hand area • sensorimotor cortex

It has been demonstrated that certain cortical functions in the central area can be localized by unique gyral and sulcal anatomical patterns. The PPM is highly correlated with functional imaging localization of hand motor and sensory functions. This landmark is recognized on axial imaging as a knob or omega sign in the middle bend of the precentral gyrus that bulges into the central sulcus. The tongue sensory region is localized in a unique triangular region at the base of the postcentral gyrus. Additionally, the lower face and lips sensory area is within the most narrowed section of the postcentral gyrus above the apex of the tongue area. Cortical landmarks that correlate with function result from consistent sulcal and gyral folding in development. Van Essen proposed axon tension to be the guiding mechanical force. Additional evidence for predictable functional and anatomical relationships is the strikingly constant association of the central sulcus with the midcallosal plane. Lehman and colleagues showed that the midcallosal line reliably intersected the inferior central sulcus. Talairach and Tournoux recognized that the central sulcus lies between 2 vertical planes extending from the anterior and posterior commissures.

Functional imaging has revealed a hand sensory and motor task activation site to be localized in a distinct anatomical landmark that is the PPM. The PPM is a cortical fold connecting the pre- and postcentral gyri that elevates the floor of the central sulcus. It lies at the apex of the middle bend of the central sulcus and is stronger on the pre-central side of the sulcus (Fig. 1). However, the primary sensorimotor hand area occupies a larger region over the pre- and postcentral gyri than just the cortical fold comprising the PPM. Cortical stimulation yields a somato-
topic relationship of finger sensorimotor responses, with
the thumb being most inferior and the fifth digit most supe-
rior along the postcentral gyrus. 33 It is interesting to note
that Penfield and Rasmussen, 33 by applying cortical stim-
ulation, identified a whole-hand sensory response as the
most common sensory response involving the hand, and it
was localized superior to the responses obtained for indi-
vidual digits, 32 consistent with the location of the PPM.
The advent of functional imaging, such as fMR imaging
and positron emission tomography, has led to the identifi-
cation of whole-hand motor and sensory activations within
the anatomical landmark of the PPM (Fig. 2). However, the
actual cortical function subserved by the PPM is not en-
tirely understood. Cortical stimulation can elicit individual
finger movements, which extend well inferior to the mid-
dle bend, with thumb movement being the most inferior-
ly located. 4,33 The stimulation studies of Penfield et al. 32,33
have shown finger movements elicited over half or more
of the precentral gyrus on the lateral convexity. Therefore,
a whole-hand motor and sensory region in the central area
would imply function redundant to individual finger so-
matotopy. Moreover, central area function identified with
cortical stimulation is not recognized to comprise complex
coordinated movements. For these reasons, the actual func-
tional role of the PPM in the central area remains uncertain.

In this study, we evaluated patients who underwent both
cortical stimulation in the region of the PPM and fMR
imaging for whole-hand motor and/or sensory activation.
Cortical stimulation responses were correlated with intra-
operative functional imaging data and postoperative imag-
ing analysis. Additionally, we observed the relationship of
the anatomical PPM with cortical stimulation responses.
The aim of the study was to elucidate the function sub-
served by the PPM and determine if the structure is truly
the substratum of a whole-hand sensorimotor function.

Clinical Material and Methods

Patient Population

Patients were identified in a prospectively maintained da-
base. Twenty-eight patients underwent craniotomy with
sensorimotor cortical stimulation mapping between July
2002 and January 2006 at West Virginia University. One
surgeon (W.B.) had performed all of the surgeries. Of these
28 patients, 14 received cortical stimulation in the region of
the PPM. Individuals who underwent both cortical stim-
ulation in or near the PPM and preoperative fMR imaging
for hand motor or sensory activation were included in this
analysis.

Data Acquisition

Magnetic Resonance Imaging. All imaging was performed
using a standard quadrature headcoil on a General Electric
Medical Systems 3T Horizon LX MR imaging unit at the
Center for Advanced Imaging at West Virginia University.
Patients were instructed to lie as still as possible, and head
movement was controlled with restrictive padding.
Functional Imaging. Blood oxygen level–dependent fMR

Fig. 1. Photographs demonstrating cadaveric brain. The PPM consists of a cortical fold connecting the pre- and post-
central gyri. It lies in the middle bend of the central sulcus and at the posterior termination of the superior frontal sul-
cus. The PPM elevates the floor of the central sulcus and is predominantly hidden within the sulcus (left). The precentral
PPM is the dominant contribution to the cortical fold and is best visualized in the cadaveric brain with the postcentral
PPM removed (center). The postcentral PPM is an obvious bulge from the postcentral gyrus that is seen with the precen-
tral PPM removed (right). Arrowheads represent the precentral gyrus PPM, and the arrows indicate the postcentral gyrus
PPM. Single asterisks indicate the superior frontal gyrus; double asterisks indicate the middle frontal gyrus.
Whole-hand sensory and motor responses

imaging data were acquired using a gradient echo spiral in–out sequence. Spiral in–out BOLD fMR imaging provided a greater signal-to-noise ratio and reduced susceptibility artifacts with the following parameters: TR 2000 msec, TE 36 msec, flip angle 70°, number of excitations 1, field of view 24 cm, matrix 128 × 128, slices 18 in the axial plane, and slice thickness 6 mm. The imaging run was completed in 3 minutes 44 seconds, yielding 108 consecutive whole-brain volumes. At the start of each run, 4 dummy excitations (that is, no data acquisition) of the spiral in–out pulse sequence were performed to establish steady-state magnetization.

Structural Imaging. The imaging session included a 3D inversion recovery spoiled gradient echo sequence (TE 1.8 msec, TR 9 msec, flip angle 15°, field of view 24 cm, matrix 256 × 256, slices 124, thickness 1.5 mm, and number of excitations 1), acquired for anatomical localization of the PPM, for use as a template on which to overlay fMR imaging activation data, and for neuronavigation during surgery.

Functional MR Imaging Activation Task and Visual Cue Presentation

Activation tasks were performed while patients lay in the MR imaging unit. Stimulus presentation was conducted using E-Prime software (Psychology Software Tools, Inc.) on a personal computer (laptop). Visual stimuli were back-projected onto a translucent screen positioned at the end of the scanner bed; patients viewed the screen through a mirror mounted on the headcoil. All patients had normal or corrected-to-normal vision; the latter state was achieved using MR imaging–compatible refractive lenses. The same visual cues were presented to the patient for both the motor and sensory activation tasks: when the scan began, patients saw a large red hexagon on the viewing screen with the
word “rest” printed in the center. After 16 seconds, a large green arrow, pointing to the right, appeared with the word “right” printed in the center. Patients were trained to rapidly tap against one another the finger and thumb of their right hand when this visual cue appeared. After 16 seconds of tapping, the “rest” sign appeared and the patients ceased tapping. After 16 seconds, a large green arrow pointing to the left appeared with the word “left” printed in the center, and patients commenced left hand finger tapping. The series was repeated for 4 complete cycles for each hand. To ensure accurate performance, patients were observed by an examiner during the finger-tapping task and were stopped and corrected, and the scan was repeated if any errors or a failure to perform the motor task was noted.

The tactile sensory task used the same visual cues, but patients were instructed not to move any body part, and the cues were used by the experimenter to perform tactile stimulation of the appropriate hand. Throughout the run, the patients lay with both hands prone and their fingers in a relaxed position (not fully extended). The experimenter applied tactile stimulation with gentle brushing of the palm and all fingers of the hand with a soft foam pad, while supporting the dorsum of the patient’s hand. Stimulation timing was triggered by visual cue onset and was identical to that described for activation of the motor system.

Functional MR Imaging Data Analysis

Data analysis was performed using the AFNI package and additional Microsoft Windows-compatible software. Preprocessing of fMR imaging data included motion correction in 3 planes using a rigid-body (6 degrees of freedom) automatic image registration algorithm. After motion correction, each fMR imaging volume was visually inspected to identify scans with residual movement. No other manipulations were performed on the functional volumes (for example, blurring, warping, or smoothing), as we did not wish to introduce any error into the anatomical localization of functional data due to interpolation, reslicing, or partial voluming. Functional brain maps were obtained by cross-correlating the BOLD response in each voxel with 1 of 5 idealized waveforms, slightly time-shifted to account for differences in the time of acquisition of the respective slice within the TR. The waveforms were the output of a convolution of the experimental time series with a gamma variate waveform to model the hemodynamic response. This process produced 2 statistics: a cross-correlation coefficient representing the temporal relationship between the task and signal change in each voxel, and the percentage of signal change observed in each voxel. To set appropriate statistical thresholds for the correlation coefficients, a Bonferroni correction was calculated. Given the average number of voxels contained in the whole-brain functional image, a statistical threshold for the inclusion of activated voxels at a probability value < 10^-7 was adopted. The peak voxel of activation was assumed to be the locus of activation in all the following fMR imaging data analyses.

Image-Guided Awake Craniotomy and Cortical Stimulation

Preoperative fMR imaging data were coregistered with the anatomical MR imaging results by using iPlan! 2.5 software (BrainLAB) via an automated image fusion algorithm. This method is an intensity-based registration that produces coaligned images in a common native space. A 3D voxel image of both data sets is computed for the transformation. A rigid-body transformation with parameters of 6 degrees of freedom for linear translation and rotation (in x, y, and z dimensions) brings the images into alignment. Similarity measures and optimization are performed to obtain the best coregistration (Fig. 2). The coregistered images were integrated into the intraoperative VectorVision image-guidance system (BrainLAB) to provide information for neuronavigation and localization of sensorimotor function that served as a guide for cortical stimulation.

Each patient’s head was immobilized with the Mayfield head clamp after injecting each pin site with a local anesthetic. The patient was positioned in the lateral or three-fourths lateral position for surgery. The patient’s head and imaging data sets were coaligned using a surface fitting z-touch device (BrainLAB) or paired anatomical point coregistration.

Surgery was performed with local anesthesia infiltration of the scalp. The patient was sedated with propofol (AstraZeneca Pharmaceuticals), remifentanil (GlaxoWellcome, Inc.), and Precedex (Abbott Laboratories) during the opening of the craniotomy and after stimulation and resection were completed. Cortical stimulation was performed with the patient fully awake. A bipolar electrode was used with a constant-current generator (Ojemann cortical stimulator, Integra LifeSciences Corp.). Stimulation parameters were 1-msec square wave, 60 Hz, and an output current of 0.5 mA increasing by 0.5-mA increments until responses were obtained. The duration of the stimulation trains were 3 seconds or less. Most responses were obtained with a current of 3–4 mA. Stimulation was initiated in the sensory tongue area (inferior postcentral gyrus) and continued along the somatotopically organized postcentral gyrus until finger and hand sensory responses were obtained. Fewer precentral stimulation attempts were made to reduce the risk of provoking a convolution. The sites of stimulation responses were marked with numbered paper tags. Letter tags indicate fMR imaging–localized function, electroencephalography, or additional mapping data.

Imaging Analysis and fMR Imaging Correlation With Cortical Stimulation

Method 1: Image-Guided Analysis. At surgery MR imaging–based guidance with BrainLAB was used to localize the fMR imaging data over the exposed cortex in the surgical field in all patients. The sensorimotor fMR imaging activation sites and the functional sites identified with cortical stimulation were marked on the exposed brain surface with paper tags, using printed characters of known size.

Digital photographs of the exposed brain were taken, with tags denoting the identified sites (Fig. 3). The intraoperative digital photographs were transferred to PowerPoint (Microsoft Corp.), and lines were drawn between the center point of the tag for fMR imaging and the center point of the tag for the corresponding stimulation response. The final magnification of each photograph was determined as the ratio between the size of the tag measured on the photograph and the original tag size. The actual distance between the fMR imaging activation and stimulation sites
was calculated by dividing the length of a connecting line measured in PowerPoint by the final magnification of the photograph.

Method 2: Extraoperative Correlation. For comparison with the image-guided method described, an extraoperative approach was used to correlate fMR imaging and cortical stimulation to minimize the errors inherent in image guidance. Image data sets consisted of co-registered anatomical MR imaging and hand sensorimotor fMR imaging data analyzed with the AFNI software. Each peak fMR imaging activation voxel was segmented as an object and displayed overlying the coregistered anatomical MR imaging data.

The peak voxel of fMR imaging activation for whole-hand sensorimotor function was within the central sulcus and deep to the gyral crown in most patients (Cases 37, 39, 42, 46, 49, and 52; Table 1). Because the surgeon only has access to the gyral crown during preresection cortical stimulation, in the 6 listed patients we performed a transposition of the segmented voxel of peak fMR imaging activation to the gyral crown in the same gyrus. The procedure was performed in the following steps: 1) voxels showing peak fMR imaging signal change were segmented as an object; 2) 3D coordinates of a cortical point representing the shortest radial distance from Step 1 to the cortical surface of the gyral crown (within the same gyrus) were identified; and 3) this point was marked for further analysis. In patients with fMR imaging peak activation over the gyral crown, a transposition was not required, and the peak voxel was simply segmented for further analysis.

The resulting image files were analyzed using Brainsight software (Rogue Research). The curvilinear application included in this software creates a 3D reconstruction of the brain surface. The surface reconstruction can be viewed at selected cortical depths at chosen increments, much like peeling the layers of an onion. Here our layer thickness was in 1-mm-steps (Fig. 4). For this analysis we used the cortical layer on which the peak fMR imaging activation data or its gyral crown transposition was visible.

Each Brainsight MR/fMR imaging cortical surface reconstruction was transferred to PowerPoint together with the corresponding intraoperative photograph. Using PowerPoint drawing tools, lines were drawn on the surgical photographs to demarcate and trace brain landmarks such as sulci and major vessels in and near the central area, and the tags labeling sites of motor and sensory hand stimulation were outlined (Fig. 5).

The landmark and tag tracings were co-aligned with the Brainsight MR/fMR imaging cortical surface reconstruction (Fig. 4) by superimposing the identical landmarks. In each patient, measurements were made between the center of the stimulation tags and the peak voxel of the corresponding fMRI activation sites or the gyral crown transposition. The measurements were corrected by the final magnification determined as the ratio between the size of the tags on the brain surface reconstruction and the original tag size.

Statistical Analysis
A t-test for the two-tailed hypothesis was performed to determine the difference between the means of Methods 1 and 2 measurements for hand sensory and motor analyses. Values are expressed as the means ± standard deviation unless indicated otherwise.

Results
Fourteen individuals underwent cortical stimulation at the PPM, and 12 (86%) experienced whole-hand motor or sensory responses. Functional MR imaging was performed...
in 9 of these 12 individuals with whole-hand motor or sensory responses to stimulation. These 9 patients, who had whole-hand motor or sensory responses documented with cortical stimulation during surgery as well as hand sensorimotor fMR imaging activation prior to surgery, are reported on in this study (Table 1). Four patients were women and 5 were men. Right-sided surgery was performed in 4 patients and left-sided in 5. The patient age at the time of surgery ranged from 20 to 67 years, with a mean age of 44 years.

Eight patients had surgery for tumor and 1 for epilepsy due to dysplasia. Whole-hand motor responses were achieved with stimulation in 7 patients. Whole-hand sensory responses were obtained in 5 patients, but the movement artifact on fMR imaging was excessive in 1 individual (Case 42) during the hand sensory task; therefore, these data were excluded from the analysis, and whole-hand sensory function was analyzed in the remaining 4 patients (Tables 1–3).

Whole-hand motor responses were clearly observed as a flexion of the entire hand except in one patient (Case 46) in whom whole-hand extension was observed (Table 1). Whole-hand sensory responses to cortical stimulation constituted a sensation elaborated by the patient to an observer during surgery. The perceived sensation was described as a feeling, tingling, or electrical-like shock in all the fingers or in the whole hand. In 3 patients both whole-hand motor and sensory responses were obtained with stimulation, always at separate sites and occurring at the expected pre- or postcentral gyrus location.

Anatomical Localization of fMR Imaging Activation

The fMR imaging activation for hand motor function was localized to the precentral gyrus PPM in the contralateral hemisphere in all patients. Hand sensory activation was localized at the level of the PPM in the postcentral gyrus in all patients, although in the posterior portion of the postcentral gyrus in 2 patients (Cases 37 and 52), 4 mm posterior to the anatomical PPM in both.
Method 1: Image-Guided Analysis. In patients with whole-hand motor responses elicited by cortical stimulation, the corrected distance between hand motor fMR imaging activation and cortical stimulation response sites ranged from 2.9 to 6.6 mm, with a mean of 4.7 mm (Table 2). In patients with a whole-hand sensory response elicited by cortical stimulation, corrected measurement values from the stimulation response site to the corresponding fMR imaging activation site ranged from 4.1 to 5.6 mm. A mean of 5.0 mm separated the hand sensory fMR imaging activation from the stimulation site.

Method 2: Extraoperative Correlation. The measured distance between whole-hand motor stimulation sites and corresponding fMR imaging activation sites ranged from 2.9 to 6.6 mm, with a mean of 4.7 mm (Table 2). In patients with a whole-hand sensory response elicited by cortical stimulation, corrected measurement values from the stimulation response site to the corresponding fMR imaging activation site ranged from 4.1 to 5.6 mm. A mean of 5.0 mm separated the hand sensory fMR imaging activation from the stimulation site.

Relationship of Stimulation to the PPM

The site of cortical stimulation for whole-hand motor and sensory responses was correlated with the anatomical PPM in each patient by analyzing coaligned anatomical MR images and the intraoperative photograph displaying stimulation response sites (Method 2). Each whole-hand sensory or motor stimulation site was within the PPM in the precentral gyrus for whole-hand motor responses and within or at the level of the PPM in the postcentral gyrus for whole-hand sensory responses.

Individual Digit Responses to Cortical Stimulation

Individual digit sensory or motor responses as well as whole-hand sensory or motor responses were identified with cortical stimulation in all but 1 patient. Ten individual digit stimulation responses were elicited separate and inferior to the anatomical PPM. Four individual digit stimulation responses were located within or at the level of the PPM. A sensation isolated to the thumb was most common. Additional responses identified were sensations in the index finger and the middle, fourth, and fifth digits. Individual finger motor responses were observed in the thumb and the fourth and fifth digits.

Isolated digit responses to stimulation were separate and distant from whole-hand sensory or motor stimulation sites. Thumb responses were elicited a mean of 14 ± 5 mm and individual finger responses a mean of 15 ± 7 mm from sensory or motor whole-hand stimulation sites.

Discussion

In this study, we have identified a whole-hand sensory and motor area in the primary sensorimotor cortex that is separate from individual finger and thumb somatotopic organization in the pre- and postcentral gyrus. In all the patients, hand sensorimotor fMR imaging activation was localized to or at the level of the PPM. The whole-hand sensory or motor function elicited with cortical stimulation was in or at the level of the PPM in all patients in the expected pre- or postcentral gyrus. Additionally, the cortical areas subserving whole-hand sensorimotor fMR imaging activation and whole-hand cortical stimulation responses were highly correlated. The anatomical PPM appears to be the cortical substratum for a whole-hand motor and sensory function that is distinct from individual finger and thumb somatotopy.

The function represented by the cortical fold of the PPM is controverted. Some authors have asserted that this small...
mean measured distance between whole-hand motor stimulation sites and corresponding fMR imaging activation was 4.4 ± 2.3 mm, and between the hand sensory stimulation sites and corresponding fMR imaging activation was 4.1 ± 2.3 mm.

(mean diameter 1.4 cm) cortical fold represents the localization of hand and finger sensorimotor function; however, this assertion is inconsistent with cortical stimulation in the human. The stimulation studies of Penfield and Boldrey and others show individual finger and thumb movements elicited over a cortical area encompassing more than the anatomical PPM in the precentral gyrus. Even prior to the work by Penfield and Boldrey on the sensorimotor homunculus, Foerster, Horsley and Schäfer, and others recognized that finger sensorimotor responses are elicited with cortical stimulation over a broad extent of the precentral gyrus on the lateral convexity, extending well inferior to the PPM. Modern reports of functional imaging and cortical stimulation have shown convincingly that the cortical region involved with individual digit function in the primary sensorimotor area occupies an area larger than the cortical fold of the PPM.

Finger and thumb movement and sensation are typically described as encompassing a region of at least the middle third of the primary sensorimotor cortex over the lateral convexity, with thumb movement being the most inferiorly located. The observations in humans are consistent with microelectrode recording and optical imaging in the primary sensorimotor area in monkeys. The primary sensorimotor area for individual digit function encompasses a larger cortical area than just the anatomical PPM.

In the hand motor and sensory fMR imaging–demonstrated tasks used herein, the activation peak represents whole-hand sensory and motor function and was not designed to demonstrate digit somatotopy. Individual digit somatotopy can be demonstrated with functional imaging by increasing the signal-to-noise ratio of the activation signal and confining the task to individual digits.

The somatotopically organized functions in the primary sensorimotor area are generally recognized to represent motion of a digit or limb, movement across 1 or 2 joints in an extremity, or sensation of a restricted somatic area, whereas more complex coordinated motor activity and regional sensory phenomena have been identified in the supplementary motor and secondary sensory areas. A whole-hand function may be too complex and coordinated to be subserved by the primary sensorimotor area. In the present study, however, 86% of the patients with stimulation at the PPM displayed a whole-hand motor and/or sensory response, data supporting a whole-hand sensory and motor area in the primary sensorimotor cortex.

A whole-hand motor and sensory area would represent function redundant with individual digit somatotopy, a situation not previously recognized in the human primary sensory and motor cortex. Sensorimotor function is organized as vertically oriented cortical columns. Each column is a bundle of neurons and fibers subserving a distinct sensorimotor function. The columnar organized neurons of the primary motor area (Brodmann Area 4) project to single motoneuron pools in the spinal cord or clusters of motoneuron pools that control groups of muscles active in similar movements. Although there is overlap among the functional columns that seems to provide the mechanism for the complex interaction between agonist and antagonist muscle groups, the activities under control of the functional column are unique. In the primary sensory cortex different modalities of sensation are correlated with cytoarchitectonic fields in the postcentral gyrus; cutaneous sensation is represented in the anterior portion of the postcentral gyrus (Area 3) and joint sensation more posteriorly (Area 2).

In the primary sensory cortex there is evidence of recurrent somatic representation, but each representation subserves a different sensory modality, and thus does not strictly duplicate function.

The correlation of cortical stimulation with fMR imaging activation in this study was done using 2 separate techniques. Method 1 consisted of a direct measurement taken from the intraoperative photograph that localized fMR imaging activation using image guidance. Method 2 involved alignment of the stimulation results on the intraoperative photograph with the fMR imaging data set. The peak voxel of functional imaging activation was assumed to be the locus of the fMR imaging–determined function.

Using Method 1, the corrected measurement for image guidance–localized fMR imaging activation to the site of cortical stimulation response yielded a mean of 4.7 mm for whole-hand motor and 5.0 mm for whole-hand sensory (Table 2).

Hand sensorimotor activation typically occurs within the central sulcus consistent with the anatomy of the precentral gyrus. Brodmann Area 4, the architectonic field that defines the primary motor area, is confined to within the central sulcus at the level of the PPM. In contradistinction, cortical stimulation can only be performed safely over the crown of the gyrus. Necessarily, a significant amount of the cortical surface remains unsampled with cortical stimulation. A measure of the Euclidean distance between the site of stimulation response and fMR imaging activation may not be an accurate evaluation of their relationship. Therefore, in Method 2, in the 6 patients with fMR imaging activation deep to the gyral crown, a transposition was performed to bring the fMR imaging activation to the surface of the cortex to better assess the fMR imaging relationship to stimulation. The analysis demonstrated a mean distance between activation and stimulation of 4.4 mm for whole-hand motor and 4.1 mm for whole-hand sensory (Table 3).

It is noteworthy that the 2 methods used to analyze the relationship between cortical stimulation and fMR imaging activation for hand sensorimotor function yielded similar results. The mean values for whole-hand motor were 4.4–
Whole-hand sensory and motor responses

4.7 mm (p = 0.8) and for whole-hand sensory 4.1–5.0 mm (p = 0.5; Tables 2 and 3). A simple measurement between image guidance–localized fMR imaging activation and the stimulation response (Method 1) produced results comparable to the more imaging-intensive coalignment of AFNI analysis and intraoperative photograph (Method 2). A previous study has revealed that the relationship of functional imaging with cortical stimulation is spatially concordant when localized within a 1-cm distance.3

Issues affecting imaging-based localization of function are errors related to image acquisition, coregistration, and image-guided surgery. An ~ 4-mm error in accuracy is inherent in the clinical use of image guidance that includes coregistration and drift.10,16,24,29 Additionally, a 6-mm slice thickness (typical for fMR imaging) was used in functional imaging for the BOLD signal in our study. With these potential errors and limitations in accuracy taken into account, the cortical sites of fMR imaging activation and stimulation responses for whole-hand sensory or motor function are highly correlated in both methods of analysis.

Stimulation response sites identified on the operative photograph were coaligned with the curvilinear reconstruction of the brain, as described in Method 2. This analysis revealed the cortical stimulation–defined whole-hand sensory or motor areas to be found within or at the level of the PPM in each patient. Similarly, we found a whole-hand sensory or motor stimulation response to be frequently elicited on stimulation at the anatomical PPM (86% of patients with stimulation in the region of the PPM), consistent with Penfield and Rasmussen’s observation that a whole-hand sensory or motor response to be frequently elicited on stimulation in the region of the PPM, consistent with Penfield and Rasmussen’s observation that a whole-hand sensory or motor response is common on stimulation in the so-called PPM, with stimulation in the region of the PPM (as defined columns—segregates—in the cat SI. J Comp Neurol 298:97–112, 1990)


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