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Functional and Dysfunctional Sensorimotor Anatomy and Imaging

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The sensorimotor system of the human brain and body is fundamental only in its central role in our daily lives. On further examination, it is a system with intricate and complex anatomical, physiological, and functional relationships. Sensorimotor areas including primary sensorimotor, premotor, supplementary motor, and higher order somatosensory cortices are critical for function and can be localized at routine neuroimaging with a familiarity of sulcal and gyral landmarks. Likewise, a thorough understanding of the functions and dysfunctions of these areas can empower the neuroradiologist and lead to superior imaging search patterns, diagnostic considerations, and patient care recommendations in daily clinical practice. Presurgical functional brain mapping of the sensorimotor system may be necessary in scenarios with distortion of anatomical landmarks, multiplanar localization, homunculus localization, congenital brain anomalies, informing diffusion tensor imaging interpretations, and localizing nonvisible targets.
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Introduction

A thorough understanding of sensorimotor anatomy and dysfunction is a desirable standard for the practicing neuroradiologist. Functional anatomy and deficit locations can be readily identified by using sulcal and gyral landmarks. These landmarks are critical in understanding and localizing the functional topography of primary sensorimotor, premotor, supplementary motor, and higher order somatosensory cortex. In addition to obvious functional deficits such as contralateral weakness and basic sensory dysfunctions, neuroradiologists should be able to localize higher order deficits of the sensorimotor system. An understanding of deficits and functional localization can affect diagnostic search patterns, imaging diagnoses, and imaging recommendations in patients with stroke, tumor, and other conditions. Understanding the functional correlates of blood oxygen level dependent (BOLD) functional magnetic resonance imaging (fMRI) activation is important in applying the technique clinically as well. In short, an understanding of the sensorimotor system can improve diagnostic accuracy at cross-sectional imaging and functional brain mapping. The following discussion addresses functional and dysfunctional anatomy of primary and higher order sensorimotor systems, related activation patterns, and brain mapping applications. Specific areas discussed include primary sensorimotor, premotor, supplementary motor, and secondary somatosensory, and posterior parietal somatosensory cortices. The reader may be surprised as to the complexity and intricacy of seemingly elementary sensorimotor functions. Tertiary networks involved in sensorimotor processing, including association, basal ganglia, thalamic, and cerebellar networks, are not fully elucidated as they are beyond the scope of this article. Cortical and subcortical substrates of cranial nerve function are discussed in the article of the same name by Agarwal et al and will not be covered here.

Sensorimotor Sulcal and Gyral Anatomy

The key to localizing motor system anatomy is an understanding of regional sulcal anatomy (Fig. 1).[1] Sulcal anatomical

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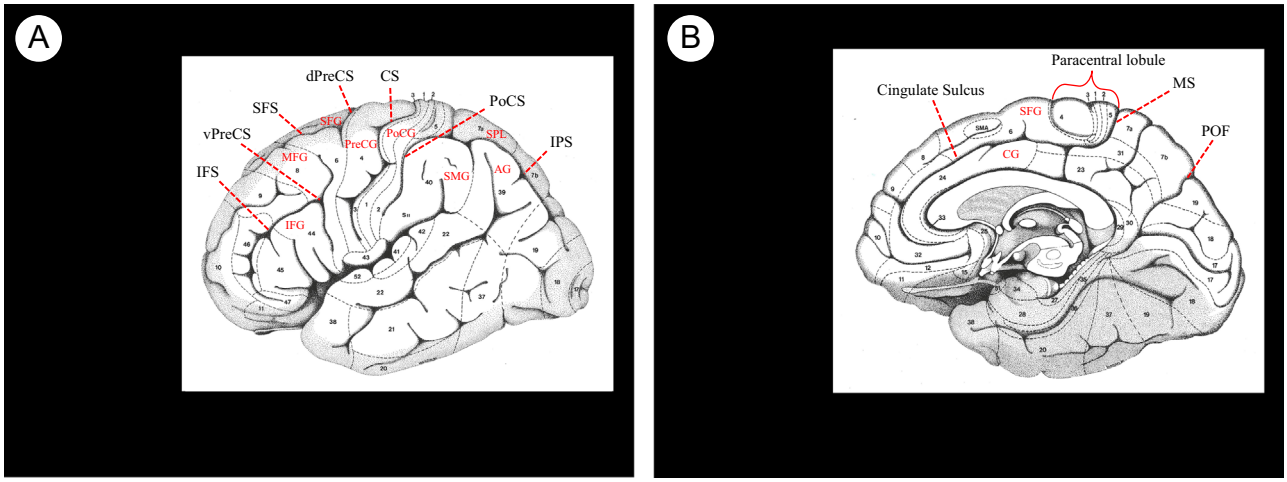

Figure 1 Lateral and medial view surface illustrations of the brain designating important sulcal and gyral landmarks and Brodmann area numbering. AG, angular gyrus; CG, cingulate gyrus; CS, central sulcus; dPreCS, dorsal precentral sulcus; IFG, inferior frontal gyrus; IFS, inferior frontal sulcus; IPS, intraparietal sulcus; MFG, middle frontal gyrus; MS, marginal sulcus; PoCG, postcentral gyrus; PoCS, postcentral sulcus; POF, parietooccipital fissure; PreCG, precentral gyrus; SFG, superior frontal gyrus; SFS, superior frontal sulcus; SMG, supramarginal gyrus; SPL, superior parietal lobule; vPreCS, ventral precentral sulcus. (Modified with permission from Duvernoy.[1]) (Color version of figure is available online.)

landmarks at imaging are more reproducible across patients than gross localization at surgery. This is because the major sulci used to define motor anatomy extend deeper into the brain than do minor sulci, which are more variable and less identifiable at cross-sectional imaging. Sulcal variations exist, but rarely involving all the relevant landmarks. Also, outside of significant brain anomalies, sulcal landmarks are mirrored across hemispheres. Thus, combining landmark data and comparing across hemispheres provides a reproducible methodology to define functional sensorimotor gyral landmarks.

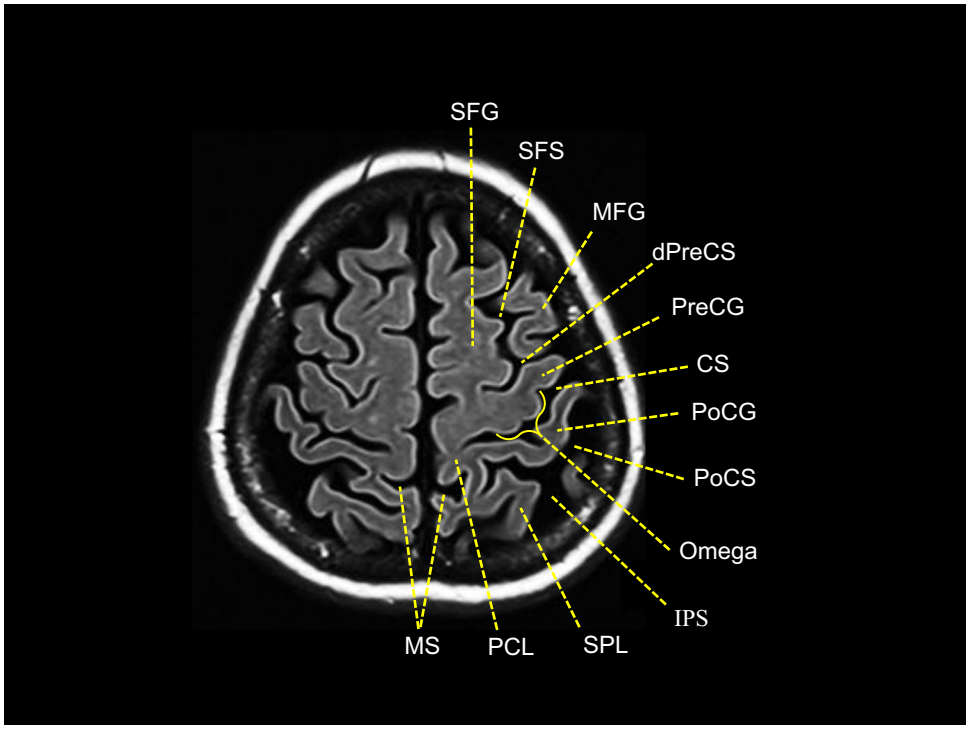

Figure 2 Axial FLAIR image showing landmarks helpful in identifying the central sulcus and sensorimotor anatomy. CS, central sulcus; dPreCS, dorsal precentral sulcus; FLAIR, fluid-attenuated inversion recovery; IPS, intraparietal sulcus; MFG, middle frontal gyrus; MS, marginal sulcus; PCL, paracentral lobule; PoCG, postcentral gyrus; PoCS, postcentral sulcus; PreCG, precentral gyrus; SFG, superior frontal gyrus; SFS, superior frontal sulcus; SPL, superior parietal lobule; Omega: omega shaped along the posterior bank of the precentral gyrus approximates the distal upper extremity MI. (Color version of figure is available online.)

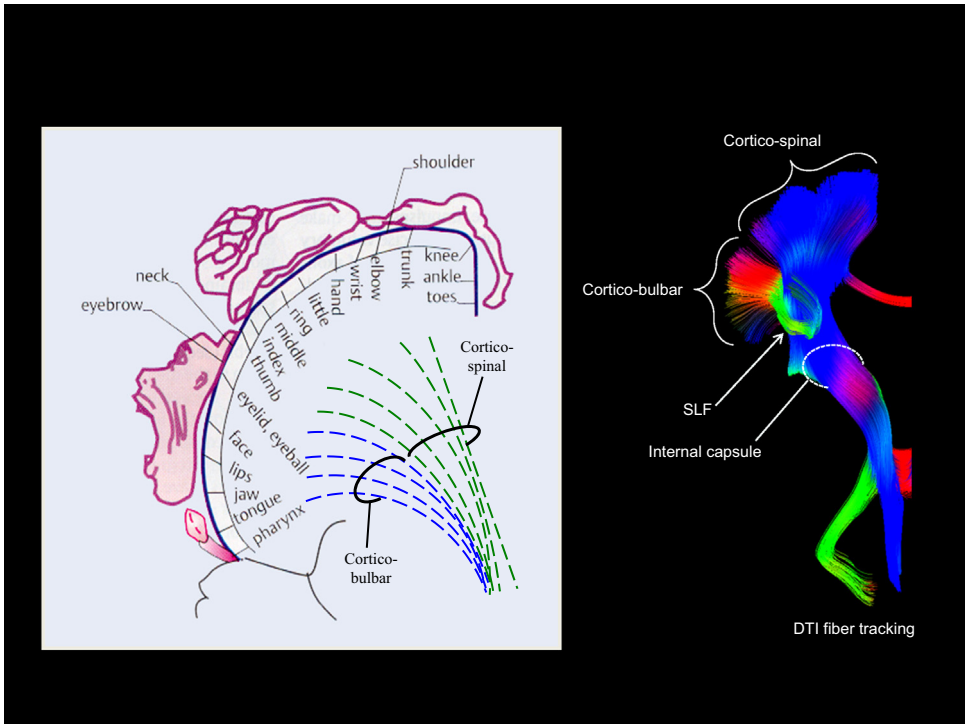

Figure 3 Cartoon representation of the motor homunculus. Fiber tracking DTI showing the relationship of motor white matter to the superior longitudinal fasciculus (SLF). Corticobulbar fibers traverse the horizontal SLF bundle as they course into the corona radiata. (Color version of figure is available online.)

The superior frontal sulcus, dividing superior from middle frontal gyrus, blindly intersects the precentral sulcus. The superior frontal sulcus is sometimes discontinuous. The precentral sulcus forms the anterior border of the precentral gyrus, and is interrupted by the middle frontal gyrus as it merges with the dorsolateral portion of the precentral gyrus. The next most posterior sulcus is the central sulcus, which divides the pre- and postcentral gyri. The pre- and postcentral

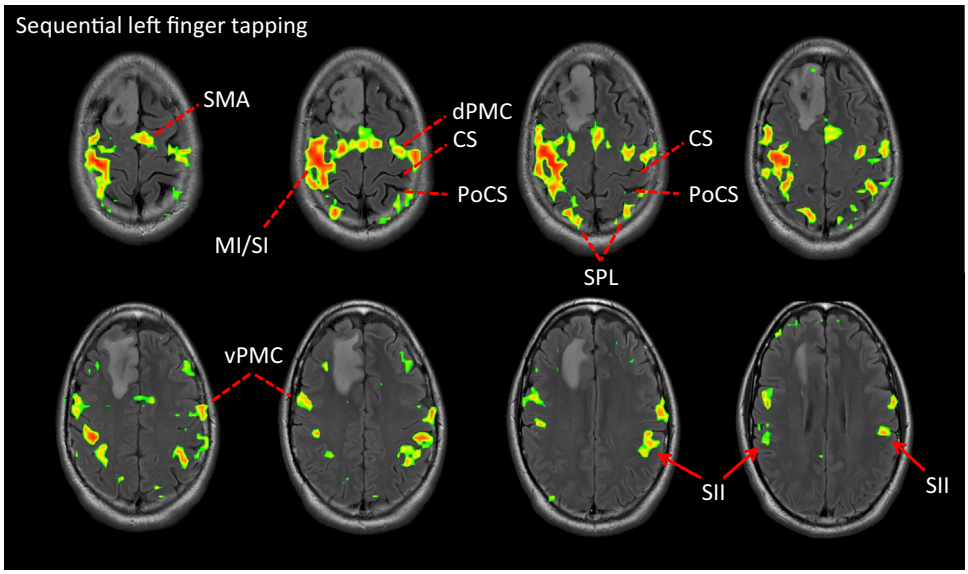

Figure 4 Interhemispheric and intrahemispheric sensorimotor system connectivity determines fMRI activation patterns. Normal unilateral sequential finger tapping activation patterns overlaid on FLAIR images are shown. Intense contralateral MI and SI activation is induced. Note the lack of ipsilateral MI activation (deactivation) and perirolandic SI activation that is too weak to reach visualization threshold. Bilateral dorsal PMC (dPMC) and ventral PMC (vPMC), and supplementary motor area (SMA) activation is shown. Bilateral secondary somatosensory (SII) and posterior parietal somatosensory cortex activation in the superior parietal lobule (SPL) is also present. CS, central sulcus; FLAIR, fluid-attenuated inversion recovery; PoCS, postcentral sulcus. (Color version of figure is available online.)

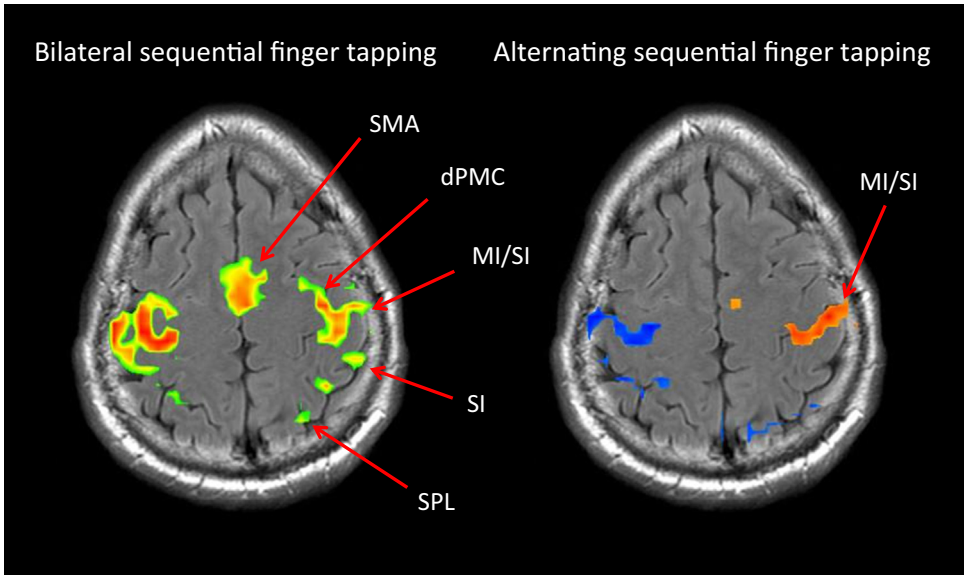

Figure 5 Alternating motor tasks can be used to distinguish MI/SI activity from higher order sensorimotor activity. Axial FLAIR images with fMRI overlays show different activation patterns for bilateral sequential finger tapping compared with alternating sequential finger tapping. Alternating sequential finger tapping eliminates bilateral activation in premotor and higher order somatosensory areas, leaving only MI/SI activity. dPMC, dorsal premotor cortex; FLAIR, fluid-attenuated inversion recovery; SMA, supplementary motor area; SPL, superior parietal lobule. (Color version of figure is available online.)

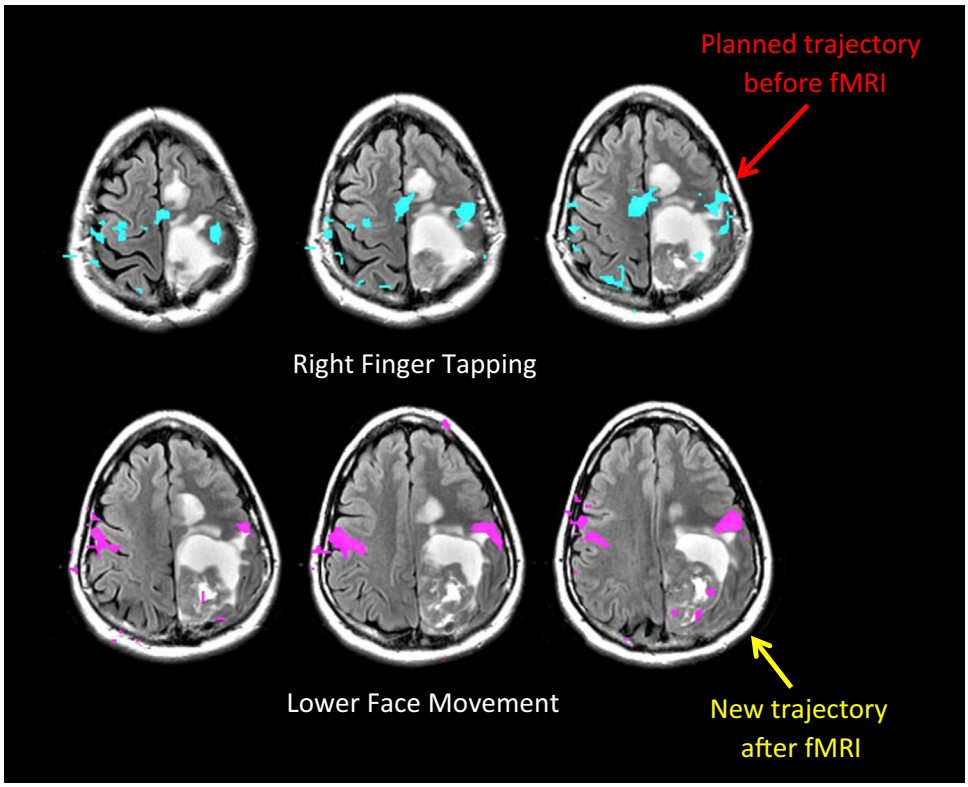

Figure 6 Tumors may distort sensorimotor anatomy, rendering localizing landmarks unusable. Axial FLAIR images are shown of a 53-year old with a brain tumor distorting sensorimotor anatomy. Identification of the central sulcus by anatomical criteria alone is problematic. Before presurgical mapping, the tumor was thought to be anterior to the central sulcus and an anterior surgical trajectory was planned. However, presurgical fMRI revealed MI/SI along the anterior-lateral tumor border, resulting in a new surgical trajectory posteriorly. The tumor was resected, without a permanent postoperative motor deficit. FLAIR, fluid-attenuated inversion recovery. (Color version of figure is available online.)

gyri merge dorsally to form the paracentral lobule and ventrally to from the subcentral gyrus (Fig. 1). The superior frontal gyrus merges with the anterior-most aspect of the paracentral lobule. The posterior border of the postcentral gyrus is formed by the postcentral sulcus, which is interrupted by the superior parietal lobe, thereby forming superior and inferior segments. The intraparietal sulcus divides the parietal lobe into inferior (supramarginal and angular gyri) and superior parietal lobules, and usually intersects the postcentral sulcus. Imaging correlates of sensorimotor sulcal and gyral landmarks are represented in Figure 2.

Functional Topography of Primary Sensorimotor Cortex

The role of the primary motor cortex is to execute voluntary movements, but is heavily guided by premotor and somatosensory input as discussed later, and by basal ganglia and cerebellar modulation.[2-4] Practiced motor acts are smoothed by the basal ganglia, which modulates the interplay between inhibition and excitation during voluntary movements. The cerebellum coordinates movements by modulating commands to motor neurons, to compensate for changes in body position or muscle load. The primary motor cortex, otherwise designated as MI, is within Brodmann area 4 (Fig. 1), lining the posterior bank of the precentral gyrus, extending deep into the central sulcus. MI is organized somatotopically as an overlapping mosaic called the motor homunculus, with corticobulbar MI located laterally, upper extremity MI located dorsolaterally, and lower extremity MI located superiormedially (Fig. 3).[2-5] The hand motor area is located on an area of redundant cortex forming an omega-shaped knuckle on the posterior bank of the precentral gyrus (Fig. 2), providing the cortical magnification needed for complex fractionated hand movements. Corticobulbar cortical magnification is also necessary to support complex orofacial movements. As the central sulcus shallows dorsally, area 4 and MI extend more to the surface of the precentral gyrus. One of the more common developmental anomalies in the perirolandic region has been termed truncation of the precentral gyrus.[6] This anomaly is characterized by truncation of the dorsolateral and lateral precentral gyrus such that the postcentral gyrus comes into proximity with the middle frontal gyrus as they wrap over the truncated precentral gyrus. This can generate uncertainty as to the demarcation between MI and primary somatosensory cortex (SI), and prevent optimal exposure during intraoperative eletrocortical stimulation.[6]

MI is responsible for executing movements, which are planned and initiated by premotor areas. Bidirectional inputs to MI include the premotor areas (supplementary motor area and premotor cortex [PMC]), primary somatosensory cortex (SI), and thalamus, as well indirect input from the basal ganglia and cerebellum via the thalamus. Direct outputs innervate to the spinal cord and brainstem motor neurons. Also, MI outputs to somatosensory cortex, premotor areas, thalamus, and basal ganglia provide the necessary feedback for motor control. Motor neuronal response properties are sensitive to complexity, rate, force, and familiarity of movements, which may affect activation patterns at fMRI.[7-17] The more complex, unfamiliar, and forceful the movement, the greater the BOLD activation will be. The effect of movement frequency on activation depends on whether or not it is cued or automatic, with the former causing greater activation and the latter causing

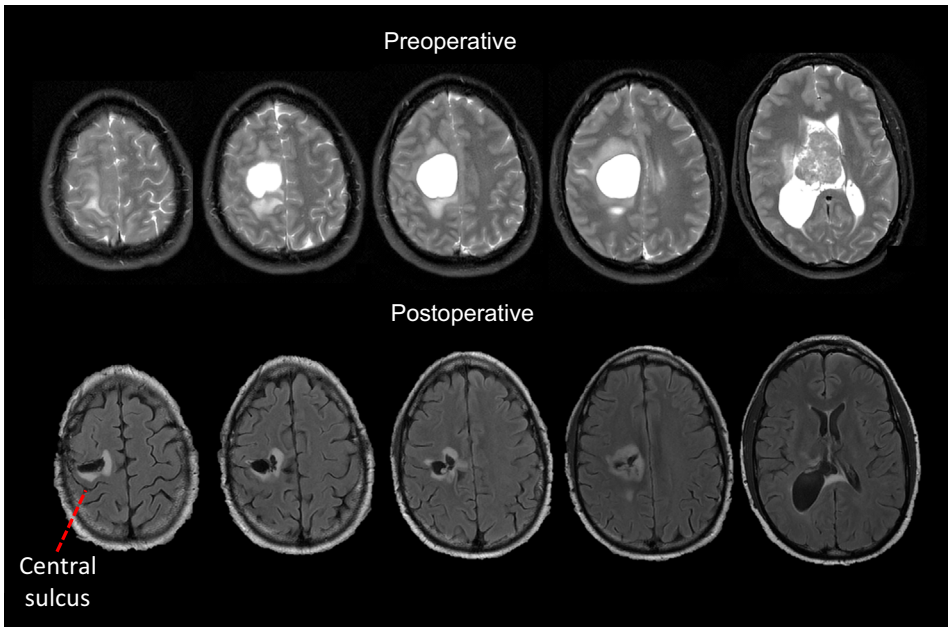

Figure 7 Preoperative axial T2-weighted and postoperative axial FLAIR images from an outside institution of the brain in a 27-year-old man with a large central neurocytoma. The central sulcus was thought preoperatively to be posteriorly displaced. A surgical trajectory was chosen using this premise. Unfortunately, preoperative fMRI was not obtained and the surgical trajectory coursed through the motor white matter, as shown on postoperative imaging. The patient was left with left upper and lower extremity paralysis. FLAIR, fluid-attenuated inversion recovery. (Color version of figure is available online.)

increasing activation with increasing frequencies. Also, activation contralateral to body movements induces ipsilateral deactivation via MI-MI callosal connections; though the effect is greater for dominant verses nondominant movements.[18,19] This modulation of ipsilateral MI by contralateral MI is somatotopically coupled and believed to be important in learning and executing complex bimanual movements by eliminating unwanted mirror movements.[20-22] Relatively low electrocortical stimulation current (30 μA) can elicit fractionated movements of body parts corresponding to the area of the homunculus stimulated.

Deficits of MI include somatotopically coupled contralateral weakness, as well as gait ataxia with involvement of the paracentral lobule.[23] Corticospinal motor functions do not recover well from injury, especially distal extremity fine movements. Gross proximal extremity and body movements will recover to some extent, owing to premotor and subcortical contributions. Corticobulbar motor functions recover nearly completely after injury, usually within several months, due to bilateral cortical innervation in the brainstem. The lateral border of the precentral gyrus omega can be used to estimate the demarcation between corticospinal and corticobulbar MI, and recovery implications of the same. Somatotopy is preserved within MI efferents in the corona radiata and internal capsule. The superior longitudinal fasciculus (SLF) approximates the location of subcortical corticbulbar efferents as they course toward the corona radiata, though some upper extremity corticospinal motor fibers may pass through the SLF as well (Fig. 3).

The role of somatosensory cortex is to provide inferences about the world and ourselves, and to guides motor movements.[2-4] The primary somatosensory cortex (SI) is located in Brodmann areas 3a, 3b, 1, and 2, in cortex lining the postcentral gyrus (Fig. 1). SI lines the anterior bank, dome,

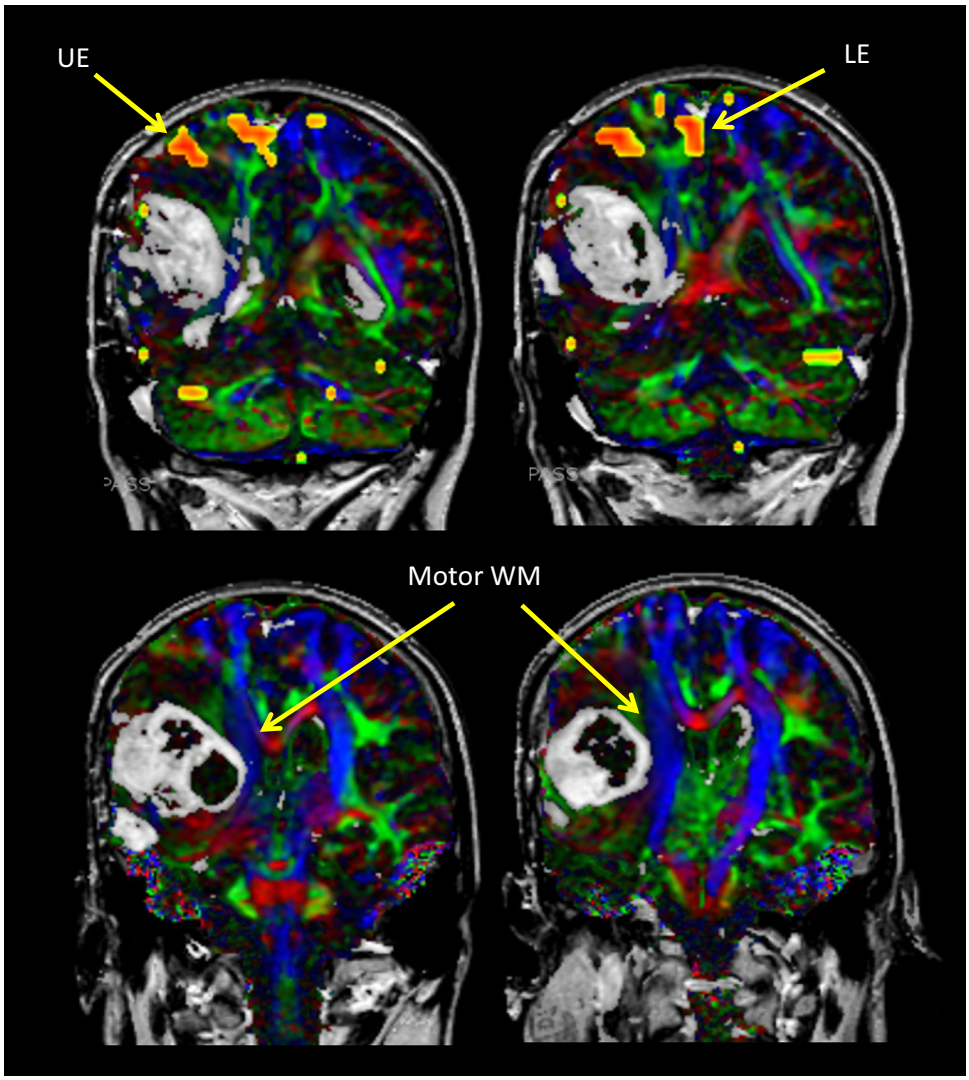

Figure 8 The relationships of motor networks to the lesion borders can be visualized by integration of fMRI, DTI and multiplanar views. Coronal images with color-coded DTI and fMRI overlays are shown. Coronal images are necessary to visualize tumor border relationships to motor networks. Unlike axial imaging, the coronal plane is not conducive to identifying anatomical landmarks for MI/SI cortex. Motor fMRI activation superimposed on anatomical coronal imaging can help identify the proximity of motor cortex to a lesion, and to localize motor white matter relationships. LE, lower extremity fMRI activation; UE, upper extremity fMRI activation; WM, white matter.

and posterior bank of the postcentral gyrus. As in MI, the hand sensory area is located in redundant omega-shaped cortex, though not as prominent as that of MI. Primary inputs to SI arise from the somatosensory thalamus (ventral posterolateral nucleus and ventral posteromedial nucleus), whereas strong outputs project to MI, premotor areas, adjacent higher order somatosensory cortex (posterior parietal cortex and SII) and basal ganglia. Outputs to the somatosensory thalamus provide the feedback necessary for cortical somatosensory modulation. Like MI, SI is somatotopically organized.[2-5] Cutaneous sensory information is processed largely in areas 3b and 1, whereas both muscle receptor and cutaneous sensations are largely processed in areas 2 and 3a. Hierarchical sensory processing occurs as information flows posteriorly from the central sulcus through Brodmann areas 3, 1, and 2.

The sensory system is not only influenced by environmental factors, but also modulated internally. SI activity has been observed before sensory input caused by movements, preceding MI activity by 150 ms.[24-27] This is thought to be initiated by dorsal PMC (dPMC) and necessary to distinguish one's own activities from those generated by external stimuli. In effect, the sensory cortex must anticipate sensory input from planned movements, to distinguish unanticipated stimuli and to guide motor reactions. Numerous connections with MI and premotor areas are critical in guiding those movements.[28,29] Movements generate BOLD activation in both MI and SI in part owing to sensory stimulation associated with the movement (Fig. 4). However, peripheral sensory stimulation alone will induce robust MI activation owing to strong corticocortical connections with MI.[28,29] Indeed, the sensorimotor homunculus can be mapped with passive movements.[30] Unilateral tasks can elicit bilateral SI activation owing to significant interhemispheric connectivity, though activation contralateral to the movement is stronger than ipsilateral activation.[31] Direct stimulation of SI cortex may elicit somatotopic paresthesias, often difficult to describe by patients. High electrical current can elicit movements owing to sparse corticospinal connections and perhaps the strong corticocortical connections with MI. Injury to SI may cause deficits in contralateral discriminative touch and joint position, and less frequently, touch,

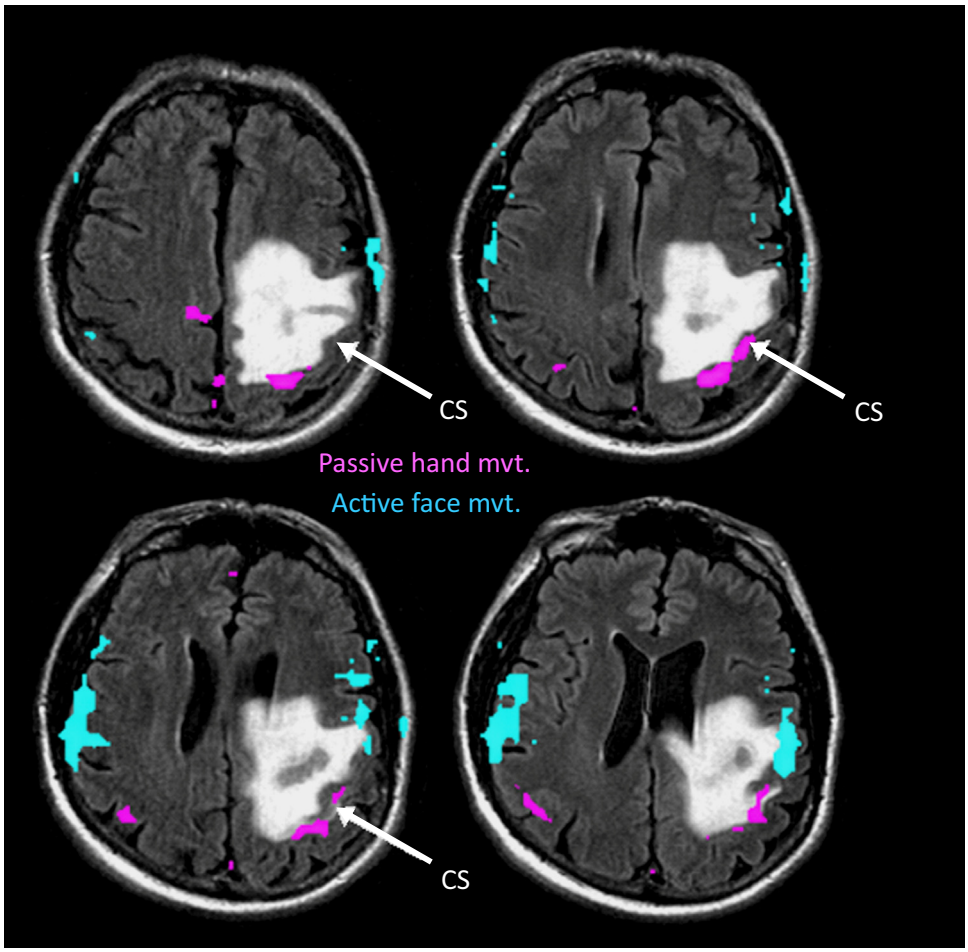

Figure 9 Passive motor mapping can localize MI in patients with lesion-induce paralysis. Axial FLAIR images are shown of a 56-year-old with a brain tumor and edema causing right upper extremity paralysis. Active upper extremity tasks or intraoperative mapping could not be used to help identify the central sulcus or MI cortex. Owing to sensorimotor corticocortical integration, passive hand movements (magenta) localized distal upper extremity MI and SI cortex showing the central sulcus posterior to the lesion. This conclusion was supported by the sensorimotor response to active lower face movement (blue). CS, central sulcus; FLAIR, fluid-attenuated inversion recovery; mvt, movement. (Color version of figure is available online.)

pain, and vibration sense.[23] Contralateral pain and paresthesia as well as decreased stereognosis and graphesthesia may also ensue. The perception of pain deserves special mention. The cognitive response to painful stimuli is processed in rostral cingulate gyrus and the insular cortex, and therefore pain can be perceived despite SI injury. SI neurons on the other hand selectively respond to sharp, cutting painful stimuli, which provides the ability to accurately localize the painful stimulus. There often are no lasting deficits from SI injury, owing to plasticity and network redundancy in other discriminative sensory areas.

Functional Topography of Premotor Areas

The role of premotor areas, including the PMC and supplementary motor area (SMA), is to plan, select and initiate complex movements, thereby guiding MI execution.[2-4,32-37] The premotor area is located within Brodmann area 6, just anterior to Brodmann area 4 (Fig. 1). Medial area 6 on the medial bank of the superior frontal gyrus contains SMA, as discussed later. Lateral area 6 is located within the posterior aspect of the middle frontal gyrus, anterior bank of the precentral gyrus, cortex surrounding the dorsal and ventral precentral sulcus, and cortex surrounding the posterior aspect of the superior frontal sulcus. The PMC is divided into dorsal and ventral cytoarchitectural regions. The frontal eye field is also located within area 6 of the human and is discussed in the article "Cortical and Subcortical Substrates of Cranial Nerve Function."

The PMC is involved in planning, selection, and triggering of complex movements, based on visual or abstract associations. It is thought to prepare MI for movement execution, activating before onset of the movement. At the same time PMC neurons can activate during a motor act or even at the mere sight of a movement as they respond to sensory input. As discussed above, the PMC is believed to project to and cue SI for planned movements. The dPMC is centered adjacent to the corticospinal representations of MI, whereas the ventral PMC (vPMC) is centered adjacent to corticobulbar MI. dPMC receives strong inputs from higher order somatosensory, visual, auditory, and temporal association cortices, and has strong connections with MI, SMA and pre-SMA, cingulate gyrus, ventral premotor area, anterolateral and ventrolateral thalamus, as well as indirect input from the cerebellum and basal ganglia via the thalamus. It also projects to the brainstem and spinal cord where it presumably directly modulates motor function, and has strong callosal connections with contralateral premotor regions. The dPMC guides complex hand and foot movements (caudal zone) and head, eye, and complex upper extremity movements (rostral zone).

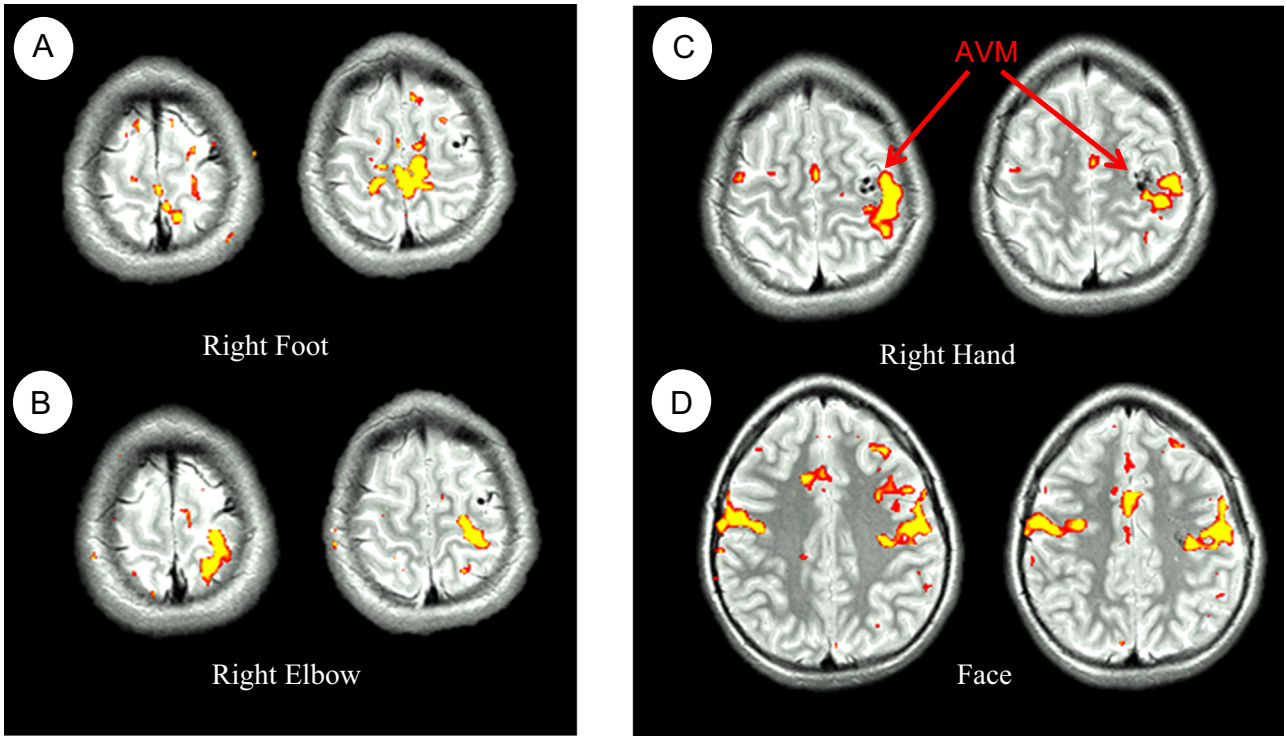

Figure 10 fMRI mapping of the subcomponents of the motor homunculus may be critical, especially when adjacent to developmental lesions. Primary sensorimotor activation for right foot (A), right elbow (B), right hand (C), and face (D) in a 13-year-old man with a precentral sulcus and middle frontal gyrus arteriovenous malformation (AVM). The patient was not a candidate for an awake craniotomy. Given the fMRI findings, the patient's distal right upper extremity function would be at high risk from surgery or embolization. The family and surgeon opted instead for gamma-knife therapy. (Color version of figure is available online.)

The vPMC guides upper extremity, head, and mouth movements and maintains memory of object locations. It is responsive to visual stimuli and tactile stimuli to the face and upper extremity, receiving input from higher order visual and somatosensory areas. vPMC also receives input from frontal and supplementary eye fields. It is interconnected with MI, SMA, dPMC, and cingulate gyrus, and also projects to the brainstem and spinal cord where it may directly modulate motor function. The vPMC is critical in guiding upper extremity reaching movements and hand movements toward the mouth, based on tactile data, visual data, or both. Activation is sensitive to behavioral aspects of motor acts, increasing with the perceived significance of the act. It is involved in maintaining the memory of object location for a short period of time even when removed from view. Thus, one can retrieve an object when turning the head to look elsewhere or turn a light switch on in the dark. Broca's area in humans is believed to be a subspecialized region of the vPMC, which may explain our natural tendencies to use hand gestures and facial expressions in verbal communication.

Unilateral motor tasks usually generate bilateral premotor cortex activation at BOLD fMRI, including the anterior bank of the precentral gyrus (Fig. 4). This should not be confused with ipsilateral MI activation. Distinguishing premotor from MI activation in the contralateral precentral gyrus can be achieved with alternating motor tasks that subtract out premotor activity (Fig. 5). Complex movements can be evoked by stimulation of the dPMC, with thresholds greater than that needed for MI. A crude topographic organization of the dPMC has been identified, with leg more medially and hand more laterally represented. Stimulation of the vPMC causes speech disturbances, and orofacial and contralateral upper extremity reaching movements. Deficits of the premotor cortex may cause limb-kinetic apraxia.[23] Dorsal premotor cortex deficits specifically may also result in compromised ability to select between competing learned conditional responses, such as that necessary to drive a car, as well as pure agraphia in the dominant hemisphere. Deficits of the vPMC specifically may also cause visual neglect and speech disturbances including motor aphasia in the dominant hemisphere and motor aprosodia in the nondominant hemisphere. Functional recoverability from deficits of the premotor cortex is generally very good, occurring within several weeks. However, deficits in selection between competing complex motor responses and speech disturbances may persist.

The SMA is located within Brodmann area 6 along the medial surface of the superior frontal gyrus (Fig. 1). The SMA and the nearby anterior cingulate cortex are important in programming and initiating complex movements, and coordinating bilateral movements, specifically initiated from memory. The SMA plays a role in guiding the force of movements to produce a desired complex movement. This area receives strong bidirectional input from the prefrontal cortex, ventrolateral thalamus, and higher order somatosensory cortex. It has strong connections with MI, dorsal premotor, pre-SMA, and adjacent motor cingulate cortices, and also sends projections to the striatum, pontine nuclei, and spinal cord. The SMA is active before and during MI execution, and is important in motor timing and flexibility. SMA is believed to play a role in motor learning as well. SMA activity precedes MI activity and is greatest with unfamiliar movements. However, activity decreases as movements are programmed in MI. Like the premotor cortex, strong callosal connections are present, which implicates the SMA in communicating movements or planned movements to contralateral motor and premotor areas. Rostral to the SMA proper is the pre-SMA, which is not strongly connected to MI. It does have strong connectivity to prefrontal, vPMC, and adjacent cingulate cortices and is more responsive to cognitive motor behavior. This area is important in planning and initiating cognitive motor behavior including speech. Supplementary and cingulate eye fields are located in the rostral SMA region and are discussed in the article "Cortical and Subcortical Substrates of Cranial Nerve Function."

SMA activity at fMRI can be generated by envisioning a complex movement, without actual execution of that movement. Likewise, pre-SMA activation can be generated with

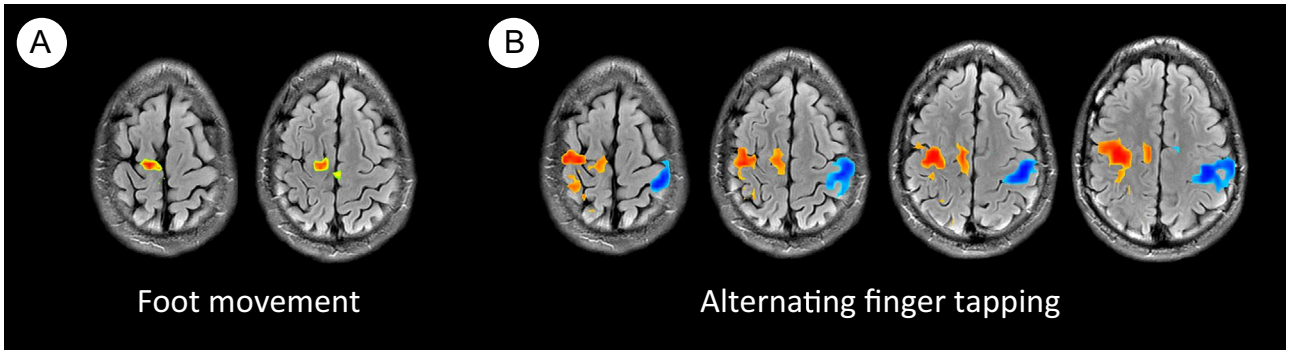

Figure 11 fMRI may localize MI cortex in the presence of gross development anomalies. Axial images of a 22-year-old right-handed man with schizencephaly and refractory seizures. EEG indicated a right frontal lobe seizures and MEG suggested that the epileptiform center was in the depth of the cleft. The patient was scheduled for intraoperative subdural electrode placement and cleft resection under general anesthesia. Axial FLAIR images with superimposed fMRI activation from a left foot motor task (A), and axial FLAIR images with superimposed alternating bilateral hand motor task activation (B) show MI within and about the schizencephalic cleft. Given these findings, the surgery was canceled. EEG, electroencephalography, FLAIR, fluid-attenuated inversion recovery; MEG, magnetoencephalography. (Color version of figure is available online.)

imagined speech, as is commonly seen with silent word generation tasks. Bilateral SMA BOLD activation in response to unilateral finger tapping precedes MI activation on the order of seconds, unlike actual neuronal activation which precedes MI on the order of milliseconds. This artifact of BOLD imaging is related to the fact that anterior cerebral artery blood flow supplying the SMA precedes middle cerebral artery blood flow supplying hand MI on the order of seconds.[38] BOLD activation within the SMA and pre-SMA is greatest with unfamiliar tasks and decreases with motor learning. In fact, the sensorimotor network at large becomes more efficient as movements become automated. Though experimental results vary, studies suggest that long-term motor training may result in reduced functional representation sites for motor and sensorimotor processing in

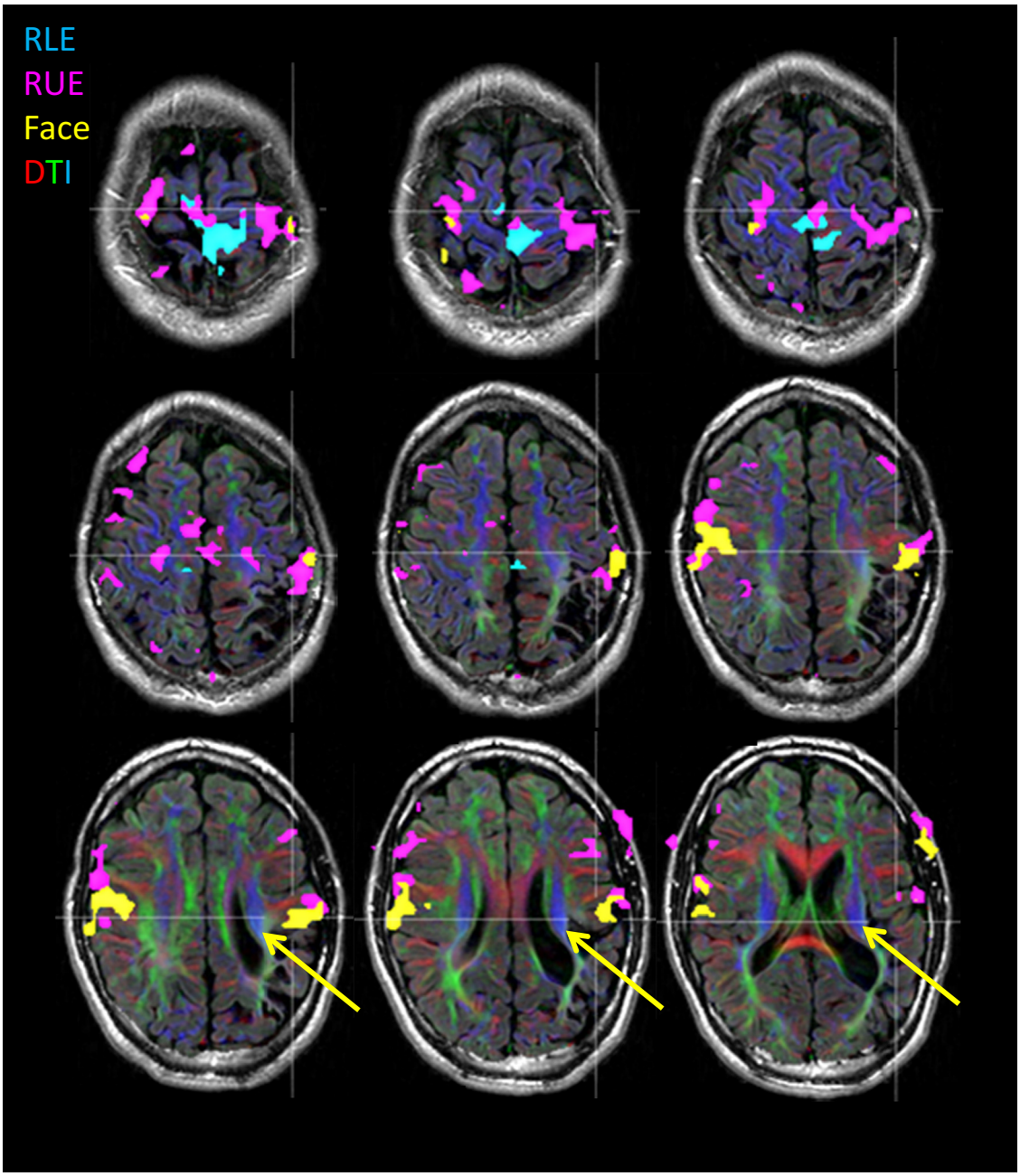

Figure 12 fMRI can inform the significance of white matter proximity to planned resection margins. Axial images of a 25-year-old man with refractory seizures from a perinatal cerebrovascular accident and mild residual right-sided weakness and clumsiness. A wide resection of encephalomalacic brain was planned. Axial FLAIR images with superimposed color-coded DTI demonstrate encephalomalacic brain tissue with close proximity to the corona radiata. Overlaid fMRI motor activation from right foot (blue), right hand (pink), and face (yellow) tasks shows no evidence of motor cortical reorganization, indicating high risk to motor networks within the corona radiata (yellow arrows) from a wide resection. Therefore, a limited resection was performed, without a postoperative motor deficit. FLAIR, fluid-attenuated inversion recovery. (Color version of figure is available online.)

ipsilateral MI, ipsilateral SI, bilateral SMA, bilateral dPMC, and bilateral superior parietal lobule as well as subcortical sites.[39-43] SMA activation associated with actual movements is generally bilateral with slight contralateral hemispheric dominance (Fig. 4), especially with dominant-sided movements.[44] The SMA contains a crude homunculus with the head representation most rostral, the foot representation most caudal, and the remainder of the body in between. Distinguishing SMA from adjacent lower extremity MI activation in the contralateral paracentral lobule may be achieved with alternating motor tasks that subtract out SMA activity.

Direct stimulation of the SMA and adjacent anterior cingulate gyrus causes the urge to move and complex contralateral movements. Higher current stimulation is required than that of MI. Stimulation of the dominant pre-SMA causes speech disturbances. Deficits of the SMA are associated with apraxia, contralateral akinesia, alien hand syndrome, and perseveration.[23] Dominant hemisphere pre-SMA deficits may cause mutism or acquired stuttering. Interestingly, acquired stuttering occurs throughout a sentence. This differs from developmental stuttering which occurs only at the beginning of a sentence. Near-complete functional recoverability from injury is expected, usually occurring within 4-8 weeks.[45] However, subtle underuse of contralateral limbs or delay in speech initiation may persist.

Functional Topography of Secondary Somatosensory Cortex

For the purposes of this article, discussions of higher order somatosensory cortex will be restricted to lateral parietal cortex

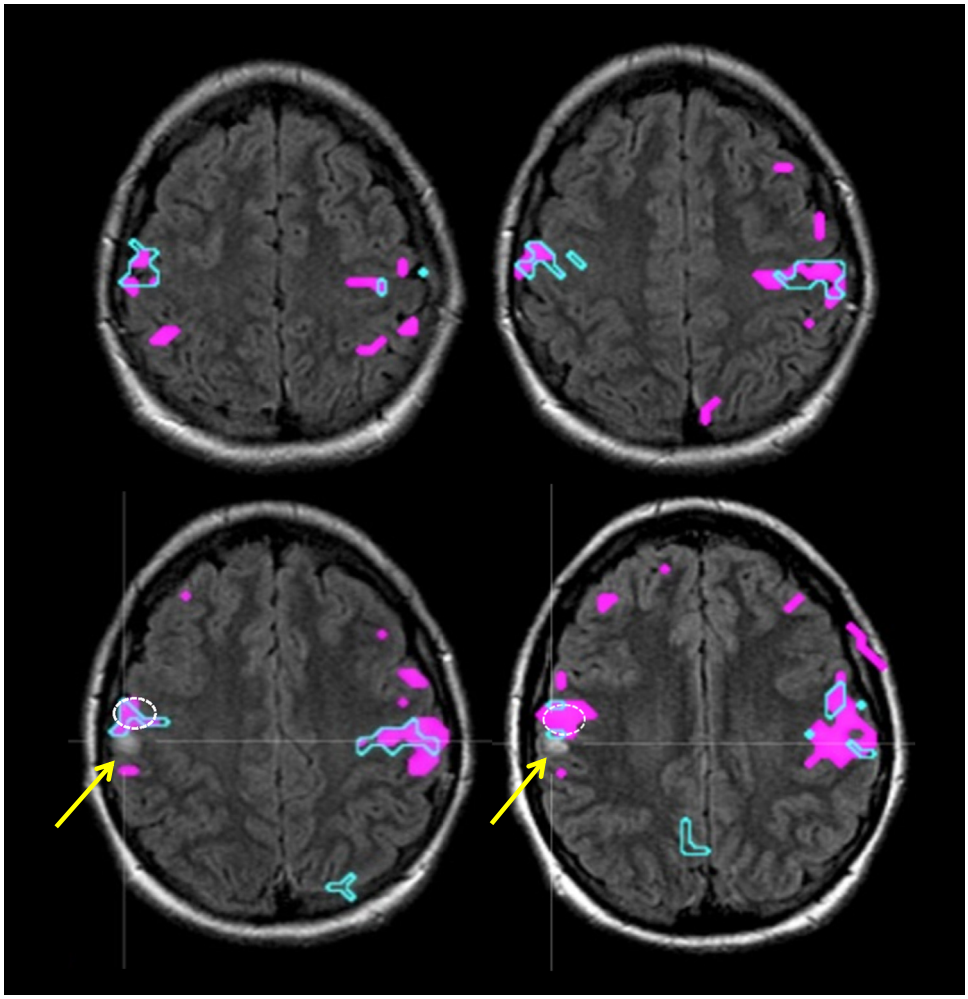

Figure 13 Integration of preoperative fMRI and intraoperative electrocortical mapping data can help to localize nonvisible lesions. Axial FLAIR images of a 15-year-old woman with headaches, episodic nausea and vomiting, showing a small left hemispheric lesion (yellow arrows). Intraoperatively, the lesion was not visible by gross inspection or intraoperative ultrasound. Axial FLAIR images with superimposed motor fMRI activation for face (blue outline) and tongue (pink fill) tasks showed that the lesion was located just posterior to tongue motor cortex. Intraoperative mapping identified tongue motor cortex (white dotted circle). A blind resection in the postcentral gyrus posterior to tongue MI successfully resected the pilocytic astrocytoma, without a postoperative motor deficit. FLAIR, fluid-attenuated inversion recovery. (Color version of figure is available online.)

in anterior area 40, and posterior parietal cortex of area 5 and adjacent portions of area 7a (Fig. 1).[2-4,46-55] A well-studied area in the lateral parietal sensory cortex is located in anterior area 40 of the inferior parietal lobule, sometimes referred to as SII. It is bounded anteriorly by SI, and sits in the parietal operculum (Fig. 1). This area receives converging inputs from areas 3a, 3b, 1, and 2 of SI as well as the sensory thalamus. It also projects to MI, PMC, insula, and association areas. It is important in guiding motor movements and the recognition and memory storage of objects and surfaces by touch. Animal studies suggest that somatosensory information is first transmitted to contralateral SI and SII cortices via the sensory thalamus, and then relayed to ipsilateral SI and SII via callosal connections from SI to SI and SII and from SII to SII for early interhemispheric integration.[47-55] BOLD activation occurs variably depending on the character of the sensory stimulus (Fig. 4), but when elicited is stronger contralateral than ipsilateral to the side of movement.[31] Because SII receives direct input from the sensory thalamus and has significant interhemispheric connectivity, it may play a role in recovery from SI deficits. Direct injury to SII may cause deficits in learning by object manipulation and in recognizing the texture and size of hand-held objects, as well as decreased topographical memory. Recoverability from injury is generally good, however.

Posterior parietal somatosensory cortex receives convergent input from the somatosensory and visuospatial systems, and is bounded anteriorly by SI and inferolaterally by the intraparietal sulcus. The posterior parietal cortex helps guide movements to targeted objects in three-dimensional space and is important in constructing a representation of objects in external space that is independent of the observer's eye or body position. This region has connections to SI, SII, the dorsal visual processing stream, anterior and posterior cingulate gyrus, MI, premotor areas, and prefrontal areas, as well as subcortical connections to the thalamus and striatum. Area 5 receives input from adjacent area 2, and represents the next step in hierarchical somatosensory processing. Area 7 is engaged in higher order visuospatial processing, attention, and retaining memory of object locations. Thus, these areas are important in integrating somatosensory (area 5) and visuospatial (area 7) data needed for motor planning, among other functions. The posterior parietal area in general integrates limb position and movement from internal cues (area 5) and visual cues (area 7). It processes sensory information important in discriminative sensations, position sense, and visuospatial orientation necessary to guide goal directed motor functions. Parietal eye fields located in this region are discussed in the article "Cortical and Subcortical Substrates of Cranial Nerve Function". BOLD activation in the posterior parietal cortex depends on the complexity and character of the sensory stimuli, but can be bilateral when elicited (Fig. 4). Injury to the posterior parietal somatosensory cortex may cause tactile agnosia, astereognosis, and graphesthesia, as well as impaired spatial relationships and optic ataxia.[23] Large lesions involving the intraparietal region and inferior parietal lobule can cause contralateral tactile, proprioceptive and/or visual neglect, and associated apraxias. Recoverability from injury is generally good unless the injured area is large or bilateral.

Clinical Applications of Motor Presurgical Mapping

The precentral gyrus and motor cortex can be readily localized with sulcal and gyral landmarks in the vast majority of patients without the need for presurgical mapping. However, there are critical circumstances requiring presurgical mapping of the motor cortex, where anatomical landmarks are insufficient to answer clinical questions that may affect surgical decision making. Preoperative motor mapping may influence resectability, surgical trajectory, establishing functional resection boundaries, and surgical target localization. In our 20-year experience in presurgical brain mapping, 6 distinct applications of presurgical fMRI localization of motor cortex have emerged.[56] Applications include lesion-induced distortion of anatomical landmarks, multiplanar localization, homunculus localization, congenital brain anomalies, informing diffusion tensor imaging (DTI) interpretations, and localization of nonvisible targets.

Identifying the central sulcus is crucial in defining the primary motor cortex. Yet, perirolandic lesions may hinder identification of the central sulcus, leaving the surgeon guessing as to which trajectory, anterior or posterior, is safest (Fig. 6). The wrong choice can be catastrophic (Fig. 7). This is particularly problematic with patients who are not candidates for intraoperative electrocortical mapping. In this scenario, it is important to map more than one area of the homunculus to demonstrate concordance of mapping data in identifying the primary sensorimotor strip. One of the more common reasons for sensorimotor mapping is to allow identification of perirolandic cortex and motor white matter in the coronal plane, where sulcal landmarks are not useful in identifying the central sulcus with confidence. This is generally applicable with planned resections of lesions deep to the sensorimotor cortex (Fig. 8). Also, active fMRI tasks and intraoperative mapping may be impossible in patients with lesion- or edema-induced motor deficits. However, owing to extensive sensorimotor integration, passive movements can be used to map motor cortex (Fig. 9).[30]

The somatotopic organization of the motor cortex is a reproducible phenomenon and can generally be estimated on the basis of gyral landmarks. However, the homunculus may be shifted in location among individuals or may be shifted on the basis of developmental anomalies. Occasionally, precise localization of somatotopic representations is important, especially with small developmental lesions nearby (Fig. 10). Gross anatomical anomalies may render identification of MI impossible as well, thereby compromising the surgical planning for epilepsy. In these scenarios, fMRI presurgical mapping can be critical (Fig. 11). Sensorimotor mapping may also be helpful in informing the significance of white matter bundles identified at DTI. This scenario generally occurs with in-utero or perinatal insults where motor cortical reorganization is possible. Establishing the preservation or loss of anatomically normal MI cortex can infer the location of motor white matter at surgical risk (Fig. 12).

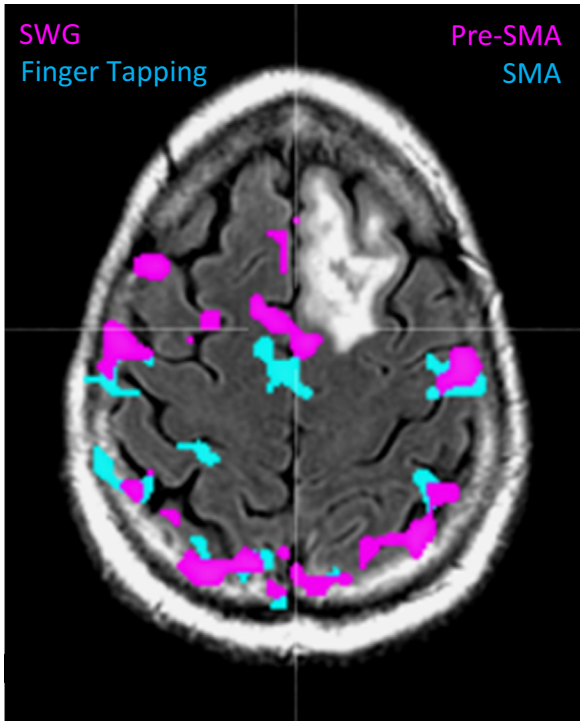

Figure 14 There are no anatomical landmarks to reliably localize the pre-SMA and SMA, yet localization of these can determine the order of tumor border dissections. Axial FLAIR image shows proximity relationships of the pre-SMA and SMA proper to the posterior medial border of a tumor, indicating risk of surgically-induced mutism. Intraoperative functional testing was also planned to preserve language networks along the lateral border of the tumor (not shown). Surgically-induced deficits of the pre-SMA will recover in a matter of weeks, but would eliminate the possibility of testing lateral language networks where deficits can be lasting. Thus, the lateral tumor margins were resected first to preserve permanent language, followed by medial tumor margins. FLAIR, fluid-attenuated inversion recovery. (Color version of figure is available online.)

Finally, fMRI mapping of the sensorimotor cortex can be useful in identifying nonvisible lesional or cortical targets. fMRI can be complementary to intraoperative electrocortical mapping in identifying a lesion beneath the cortex that is otherwise too small to be evident visually or with intraoperative ultrasound. In other words, the concordance between preoperative mapping that has known proximity to a small lesion and intraoperative mapping that can be visualized during surgery can be used to estimate the location of a lesion (Fig.13). The boundaries of premotor and secondary somatosensory cortex cannot be estimated with the same precision as MI or SI by anatomical landmarks alone. One common application of fMRI is the identification of the SMA and pre-SMA. Although surgically-induced deficits of the SMA or pre-SMA will recover in a matter of weeks to months, such deficits will eliminate the possibility to test speech or motor functions intraoperatively. Thus, establishing lesion border-SMA and pre-SMA relationships preoperatively can determine the order of lesion border dissections so as not hinder testing needed to preserve nonrecoverable motor or language functions (Fig. 14). An additional application of sensorimotor mapping is the localization of cortex for epidural electrode placement in functional Neurosurgery cases where the cortex is not directly viewable by virtue of intact dura and intraoperative electrophysiological localizations methods are inadequate owing to current spread. In our experience, fMRI can localize MI within a few millimeters of therapeutic electrode placement.[57]

Conclusion

In summary, presurgical sensorimotor mapping can be important in distortion of anatomical landmarks, multiplanar localization, homunculus localization, congenital brain anomalies, informing DTI interpretations, and localizing nonvisible targets. Key steps to translating functional mapping of the sensorimotor system include understanding functional anatomy, deficits caused by surgical injury, and recoverability of sensorimotor systems. Though not discussed here, motor white matter mapping with DTI is equally as important.[58] Presurgical mapping of the sensorimotor cortex is a vital service in institutions where perirolandic surgeries are performed. Neuroradiologists should be versed in motor mapping to support Neurosurgical services and minimize postoperative motor deficits.

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