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CASE REPORT

Presurgical and Intraoperative Mapping of the Motor System in Congenital Truncation of the Precentral Gyrus

SUMMARY: A 43-year-old man presented with a grade II astrocytoma in the left postcentral gyrus and superior parietal lobule. Preoperative functional MR imaging and diffusion tensor imaging mapped distal upper-extremity primary motor cortex and white matter, respectively, adjacent to the tumor, within a congenitally truncated precentral gyrus. Because of the congenital anomaly, this region of primary motor cortex was inaccessible to direct visualization or intraoperative electrocortical stimulation. The integration of preoperative and intraoperative mapping data facilitated resection of the tumor while avoiding a postoperative motor deficit.

Validation studies have shown good correlation between blood oxygen level–dependent (BOLD) functional MR imaging (fMRI) cortical mapping and electrocortical stimulation.[1,2] Intraoperative mapping, however, may reveal eloquent cortex not identified by fMRI, as a consequence of lesion-induced neurovascular uncoupling disturbing the BOLD contrast mechanism.[3,4] On the other hand, intraoperative mapping techniques are limited in identifying eloquent cortex that line sulci deep within the brain. Intraoperative mapping of eloquent white matter has shown promise[5] but as a technique is not as well established as cortical mapping. We present a case where fMRI demonstrated adjacency of distal upper-extremity primary motor (M1) cortex to a glioma that was not accessible at intraoperative electrocortical stimulation. Diffusion tensor imaging (DTI) revealed the relationship of motor white matter fibers to deep tumor borders. The case presented here emphasizes the importance of recognizing a relatively common variant, a truncated precentral gyrus, in neurosurgical patients and illustrates the complementary nature of intraoperative and preoperative brain mapping techniques.

Techniques

fMRI

The functional data were collected with a 1.5-T scanner and a single-shot gradient echo-planar sequence with the following parameters: (repetition time/echo time [TR/TE], 3000/50; flip angle, 90°; field of view (FOV), 24 cm; 64 × 64 matrix; 28 sections; and 5-mm-thick sections. Activation maps were constructed by using an automated functional neuroimaging (AFNI) program (RH Linux 6.0),[6] by using a correlation coefficient threshold of 0.5 ($P < .001$) and motion correction. Activation maps were superimposed onto postcontrast 3D spoiled gradient recalled-echo (SPGR) anatomic images for gyrus localization, with the following parameters: TR/TE, 25/3; fractional anisotropy (FA), 30; FOV, 24 cm; 256 × 256 matrix; 124 sections; and 1.3-mm section thickness. Activation maps were also superimposed onto axial fluid-attenuated inversion recovery (FLAIR) images to visualize the full extent of tumor in relation to the areas of activation, with the following parameters: TR/TE, 10002/158; TI, 2200; FOV, 24 cm; 256/192 matrix; 28 sections; and 5-mm section thickness.

Functional Paradigms. On the basis of an anatomic analysis of the relationship among tumor borders and eloquent gyri observed on the presenting MR imaging, functional paradigms were chosen to encompass the corticospinal motor system, by mapping distal upper- and lower-extremity M1 cortex. Self-paced right sequential finger tapping was used to activate distal upper-extremity M1 cortex. This task typically activates primary sensorimotor, supplementary motor area (SMA), other premotor area, and secondary somatosensory cortices. Right ankle movement was used to map distal lower-extremity M1 cortex. This task typically results in sensorimotor activity in the paracentral lobule that is slight compared with that observed from finger tapping, because of the crude, nondexterous nature of the task and the limited range of ankle joint motion that can be elicited without causing head motion. Thus, the activation observed in the paracentral lobule in response to ankle movement is often assumed to be an underestimate of the full area of the sensorimotor cortical field. This task also typically activates SMA and secondary somatosensory cortex, and inconsistently activates other premotor areas.

DTI. DTI data were acquired by using a spin-echo, echo-planar sequence with the following parameters: TR, 6000; FOV, 24 cm; 64/64 matrix; 18 sections; 5-mm section thickness (contiguous), with b value = 1500 s/mm^2 and gradient encoding in 25 directions. FA images and direction-sensitive color-coded maps were generated to distinguish white matter bundles that included the superior and inferior fronto-occipital fasciculi, the superior and inferior longitudinal fasciculi, cingulum, uncinate fasciculus, internal capsule tracts, brain stem tracts, and the corona radiata containing corticospinal, corticobulbar, and corticopontine tracts. FLAIR and fMRI images were acquired in identical section locations for comparative use.

Case Report

A 43-year-old man presented with a 3-year history of intermittent seizures characterized by right lower-extremity pain and followed by right lower-extremity numbness lasting several minutes. Brief episodes of right upper-extremity pain were also noted during the intermittent seizures. MR imaging revealed a well-defined tumor centered

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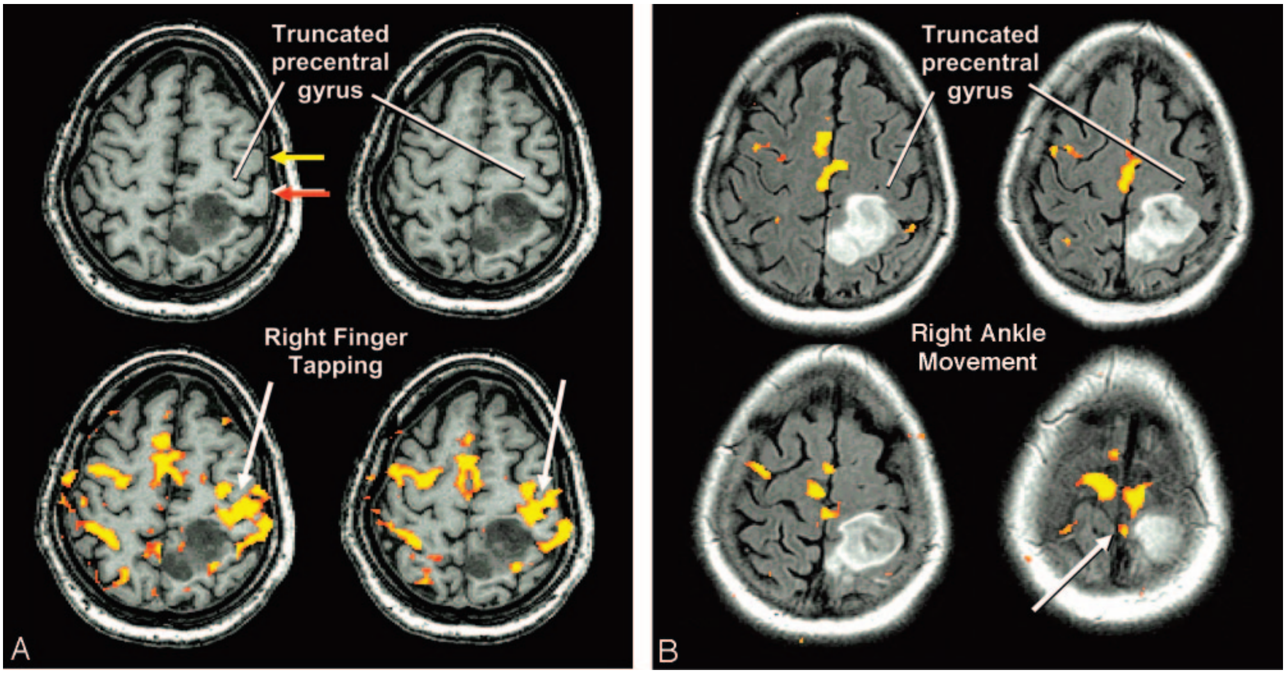

Fig 1. *A,* Axial SPGR images showing truncation of the left precentral gyrus (*upper row*) and activation to sequential finger tapping (*white arrows*). The left postcentral gyrus (*red arrow*) extends anteriorly around a truncated precentral gyrus, and comes near the posterior aspect of the left middle frontal gyrus (*yellow arrow*). Nearly continuous activity spanning from truncated precentral gyrus to overlapping postcentral gyrus is notable. Demarcating the boundary between M1 and S1 cortex is not possible at preoperative functional MRI (fMRI). *B,* Activation (*white arrow*) to right ankle movement is shown superimposed onto fluid-attenuated inversion recovery (FLAIR) images, yielding only slight activity. Slighter than typically observed activity to the lower-extremity task may be due to a combination of tumor-induced neurovascular uncoupling and the limitations of the task, and probably underestimates the actual distal lower-extremity M1 cortical field. In *A* and *B,* the proximity of eloquent lower-extremity and upper-extremity M1 cortex to the anterior-medial and anterior-lateral borders of the mass, respectively, are notable.

in the left postcentral gyrus and superior parietal lobule in concordance with his symptoms. The mass displaced the paracentral lobule and the central sulcus anteriorly. BOLD fMRI revealed M1 cortical function in response to right ankle movement and sequential finger-tapping tasks to be located immediately adjacent to the anterior-medial and anterior-lateral borders of the mass, respectively (Fig 1). Based on known somatotopic relationships, displaced intervening precentral gyrus situated between these 2 regions was assumed to contain the remainder of corticospinal M1 cortex, an assumption supported by intraoperative cortical mapping. Thus, the entire corticospinal cortex was at risk for injury associated with an intended complete resection of the mass.

DTI revealed upper- and lower-extremity corticospinal fibers to be located adjacent to the anterior-medial and anterior borders of deeper portions of the mass, respectively (Fig 2). MR imaging revealed a common congenital configuration characterized by truncation of the left precentral gyrus, specifically in the region of left upper-extremity M1 cortex and associated descending corticospinal fibers (Fig 1 and 2). This portion of the left precentral gyrus did not reach the surface of the brain but was hidden from view by an overlapping left postcentral gyrus, which opposed the posterior-most aspect of the left middle frontal gyrus. The result of this configuration was that upper-extremity M1 cortical activation demonstrated at fMRI was not accessible to intraoperative cortical stimulation (Fig 3). Thus, resection of deeper portions of the tumor required dissection planes close to unseen M1 cortex and to motor fibers arising from the truncated gyrus.

A waking procedure was performed to resect the left parietal lobe mass. Electrocortical stimulation (8 mAs) revealed proximal upper-extremity motor function within the upper precentral gyrus (Fig 3). The portion of the precentral gyrus activating at fMRI to finger tapping, however, was hidden by an overlapping postcentral gyrus. Stimulation of a relatively diffuse region of the anterior lip of the overlapping postcentral gyrus resulted in hand movements (Fig 3). Without preoperative brain mapping, this region of the postcentral gyrus may have been assumed to represent the full extent of the hand-area M1 cortical field. Stimulation of the posterior aspect of the left postcentral gyrus resulted in sensory effects of the right upper extremity (Fig 3). The tumor was carefully dissected away from eloquent gray and white matter structures while relevant motor functions were monitored. For example, upper-extremity motor functions were monitored during dissection of the anterior-lateral border of the tumor that was shown preoperatively to be adjacent to M1 cortex in the truncated precentral gyrus. Resection of the medial and anterior portions of the mass resulted in transient intraoperative lower-extremity weakness, which is believed to be a result of the proximity of the corticospinal tract to this portion of the tumor as shown on DTI. The patient experienced no permanent deficit of motor functions. Histologic analysis revealed the mass to be grade II astrocytoma.

Discussion

BOLD fMRI has gained acceptance as a valuable tool to map eloquent cortex of the motor system preoperatively.[7,8] A newer mapping technique, DTI, has shown promise in identifying the spatial relationships between eloquent white matter and resectable lesions.[9,10] The integration of these data has the potential to estimate the location of functional networks preoperatively.[11] fMRI generally correlates well with intraoperative electrocortical stimulation in identifying the spatial relationships between eloquent cortex and brain tumor borders.[1,2] Cases have been reported, however, in which lesion-induced neurovascular uncoupling results in an underestimation of genuine neuronal activation, by disturbing the

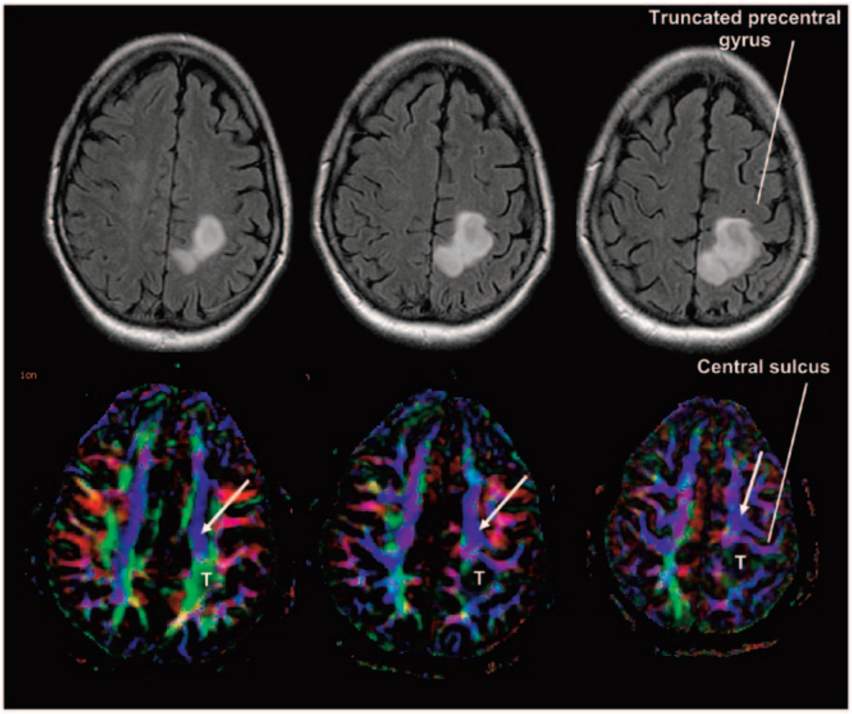

Fig 2. Axial FLAIR (*top row*) and color-coded FA maps (*bottom row*) demonstrating the proximity of the tumor to corticospinal fibers. The color-coded FA maps hinder visualization of the tumor, which implies preserved FA and function of involved white matter tracts. Thus, comparing FLAIR images to the color-coded FA maps is critical in fully appreciating the proximity of tumor borders to motor fibers. Based on anatomic relationships and DTI data, the white matter arising from lower-extremity M1 cortex wraps around the anterior-medial edge of the mass, whereas white matter descending (*blue*) from upper- and lower-extremity M1 cortex (*arrows*) is in proximity to the anterior border of the mass. White matter arising from corresponding postcentral gyrus wraps around the anterior-lateral border of the mass. In light of the results of the intraoperative mapping, it is possible that postcentral gyrus white matter contains motor fibers. T, tumor. White matter orientation color encoding: blue, ascending-descending fiber orientation; red, right-left fiber orientation; green, anteroposterior fiber orientation.

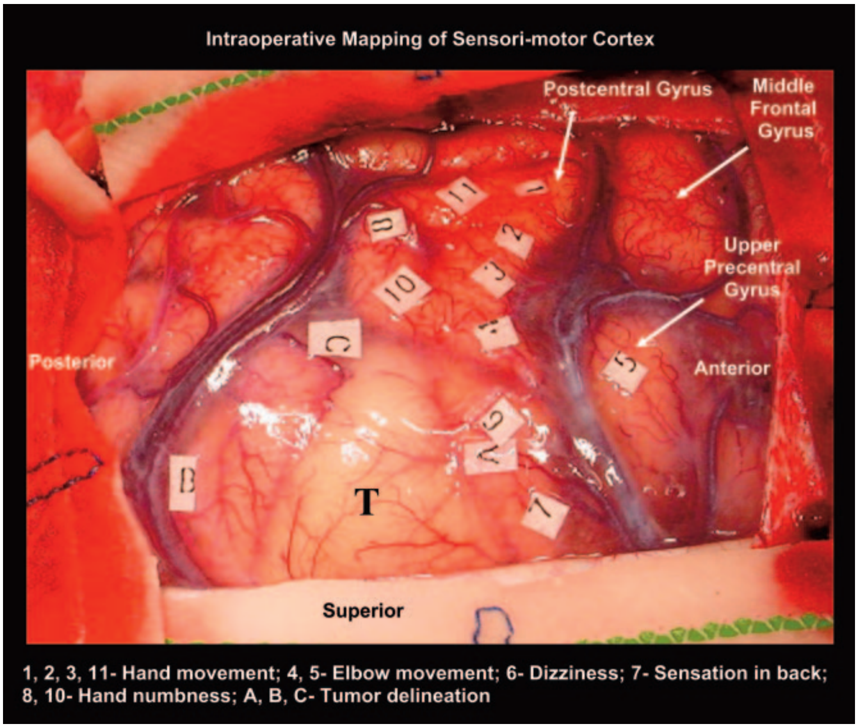

Fig 3. Intraoperative images of the brain tumor outlined by sonography and demarcated on the surface by letters *A, B,* and *C.* The postcentral gyrus extending anteriorly to approximate the posterior border of the middle frontal gyrus, hiding the superior-lateral portion of the precentral gyrus from view, is notable. Electrocortical stimulation of the upper precentral gyrus (position 5) resulted in proximal upper-extremity movement. Electrocortical stimulation at positions 1, 2, 3, and 11 within the anterior aspect of the postcentral gyrus resulted in hand movements. Electrocortical stimulation at positions 8 and 10 in the posterior aspect of the postcentral gyrus resulted in right-hand numbness. Stimulation at position 7 within the postcentral gyrus involved by the tumor resulted in a reproducible abnormal sensation of the upper back. T, tumor beneath visible cortex.

BOLD contrast mechanisms in fMRI.[4,5] Intraoperative electrocortical stimulation, on the other hand, is limited by accessibility to deeper functional cortical regions, such as those lining deep sulci. This might include M1 cortex lining the posterior bank of the precentral gyrus or speech cortex deep within the frontal operculum. Intraoperative mapping of functional white matter has shown promise as well,[5] but it is not widely used.

The sensorimotor cortex is somatotopically organized within the postcentral and precentral gyrus, respectively.[12] Textbook descriptions of the sensorimotor homunculus are misleading, in that they imply discreet divisions between somatotopic cortical areas and between primary sensory and motor cortex.[12-14] Rather, sensorimotor somatotopy is organized in an overlapping mosaic of integrated cortical fields.[13-16] Likewise, the sensory and motor system is characterized by extensive corticocortical connections, assuring the integration of these functional regions.[7,13,15,16] Although most subjects show typical somatotopic sensorimotor relationships, the exact position of a given body part within the homunculus may be shifted from subject to subject.[7,13,16] Anatomic landmarks[15] can only approximate somatotopic sensorimotor relationships. Consequently, both fMRI and electrocortical stimulation can be important tools to identify eloquent M1 cortical regions on a case-by-case basis in patients with brain tumors and other resectable lesions.

Patterns of activation within the sensorimotor homunculus at fMRI reflect the overlapping and integrated nature of the cortical fields.[7,13] In addition, sensorimotor corticocortical connections can cause motor or sensory tasks to activate both sensory and motor cortex lining the central sulcus, as well as sensory cortex in other regions of the postcentral gyrus. Distinguishing the exact boundaries between primary sensory (S1) and motor (M1) cortex is not possible with fMRI. Nevertheless, the assumption is commonly made that activity of the posterior bank of the precentral gyrus represents M1 cortex and activity in the anterior bank of the postcentral gyrus represents S1 cortex.[7]

In the case presented here, a not infrequently seen congenital variant characterized by truncation of the superior-lateral portion of the precentral gyrus hindered complete intraoperative mapping of eloquent upper-extremity M1 cortex. Unnecessary transection of the pia and manipulation of a large cortical vein may have been required to reach the relevant unmapped portion of the precentral gyrus (Fig 3). The postcentral gyrus wrapped over the lateral aspect of the precentral gyrus at this location, nearly contacting the posterior aspect of the left middle frontal gyrus. Consequently, only the more superior and inferior most portions of the precentral gyrus were visible at surgery and accessible to intraoperative mapping. Yet, fMRI demonstrated proximity of distal upper-extremity M1 cortex in the truncated portion of the precentral gyrus to the anterior-lateral edge of the tumor. Deeper dissections of this tumor border could therefore put at risk M1 cortex and motor fibers arising from this region, without the benefit of direct surface visualization. In light of the poor potential for reorganization of distal upper-extremity motor function,[5] this observation was especially important. Because the visualization of this region was limited by the patient's anatomy, special care was taken during functional testing to dissect this portion of tumor away from adjacent eloquent gray and white matter carefully.

At our institution, neurologic risk assessment and surgical planning depend on the integration of information derived from the clinical presentation, anatomic spatial relationships shown at MR imaging, presurgical functional mapping at fMRI and DTI, intraoperative cortical mapping, and intraoperative functional assessments. Presurgical mapping can be crucial to risk assessments and in establishing the safest surgical approach. In some cases, this information may alter the surgical trajectory or determine the extent of tumor resection, particularly when a patient is not a candidate for a waking procedure; however, even when a waking procedure is planned, presurgical mapping and intraoperative functional assessments are complementary.[4] The goals of presurgical mapping and intraoperative functional assessments are to identify tumor borders adjacent to key functional systems, to avoid those eloquent areas at surgery where possible, and to dissect away tumor borders identified near eloquent areas while monitoring relevant functional capabilities of the patient.

The ultrasonic aspirator used at our institution provides an unexpected advantage to neurosurgeons in that it will cause temporary neuronal dysfunction immediately adjacent to the resection margin, which can be detected with functional testing during surgery. This feature facilitates a natural synergy between preoperative and intraoperative localization strategies. The increments of tissue removal and knowing when and which functions to test during a given tumor border dissection can depend on the spatial relationships established at presurgical mapping. Although resection margins will typically extend slightly beyond tumor borders into noneloquent brain, a temporary intraoperative neurologic deficit will often establish the limits of dissection adjacent to eloquent tissue. Thus, presurgical mapping with fMRI and DTI enables the more effective use of intraoperative localization strategies. The integration of complementary presurgical and surgical techniques has reduced permanent operative speech and motor deficit rates in posterior left frontal lobe tumor patients by 5-fold at our institution.[17] Our preliminary outcomes analysis for all tumor locations in patients receiving preoperative fMRI and DTI suggests a 4% neurologic complication rate from tumor resections,[11] which compares favorably to complication rates of 7%–26% reported in the literature.[18] Our complication rate, however, will need to be confirmed with larger studies.

It is well known that stimulation of the postcentral gyrus can cause motor movements. It has been suggested that this is due to direct corticospinal connections arising from the postcentral gyrus.[13,15,16] In our case, stimulation of the anterior bank of the postcentral gyrus overlapping the truncated portion of the precentral gyrus resulted in hand movements. Stimulation of the posterior aspect of the same postcentral gyrus resulted in sensory effects of the right upper extremity. It is possible that truncation of the precentral gyrus was associated with extension of the M1 cortical field needed for fine movements of the hand to the anterior portion of the postcentral gyrus. Differentiating the boundary between primarily S1 and primarily M1 cortex was not possible at fMRI in this case. This has important implications, because the presence of postcentral gyrus motor cortex would indicate that white matter arising from that gyrus would contain motor fibers, and these fibers were shown by DTI to be immediately adjacent to or involved by the tumor (Fig 2). On the other hand, it is also possible that direct postcentral gyrus corticospinal connections and/or sensorimotor corticocortical connections resulted in the motor effect induced by electrocortical stimulation of anterior postcentral gyrus.[13,16] Because no transient or permanent upper-extremity motor deficit occurred during resection of this portion of the tumor, the latter explanation for the intraoperative mapping results seems most appropriate.

Still, fMRI revealed adjacent distal upper-extremity primary motor cortex that was not accessible to electrocortical stimulation, thereby facilitating a safe resection. Intraoperative electrocortical stimulation identified proximal upper-extremity M1 cortex adjacent to the tumor. DTI revealed corticospinal motor fibers adjacent to the anteromedial and anterior border of the tumor. Intraoperative functional testing helped to confirm the location of eloquent brain tissue and determine the extent of resection of tumor borders. The fMRI and DTI data available preoperatively and intraoperative localization strategies were each important in avoiding a motor deficit. This case illustrates that preoperative brain mapping techniques, such as fMRI and DTI, and intraoperative localization techniques are important complementary strategies that can facilitate the safe resection of brain tumors in close proximity to eloquent gray and white matter structures. More important, truncation of the precentral gyrus is not a rare variant and the observation even on routine CT and MR imaging of a surgical lesion in proximity to a truncated precentral gyrus should be noted in neuroradiology clinical reports to alert our neurosurgery colleagues.

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In this issue of the *AJNR* the first in a series of cases illustrating and describing the use of presurgical mapping by using advanced neuroimaging techniques is presented. Each case will detail those techniques used in the acquisition and subsequent postprocessing of the data used in operative planning. How they correlate with the routine imaging and the findings at surgery will be emphasized. There will be approximately 3 such articles per year, each demonstrating the efficacy of these techniques. The series has been organized by Dr. John Ulmer, of the Medical College of Wisconsin, in conjunction with his colleagues in the newly formed American Society of Functional Neuroradiology. It is anticipated that continued advances in functional MR will eventually make these techniques part of the imaging work-up in selected patients with intracerebral masses.

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