Preoperative Functional MR Imaging Localization of Language and Motor Areas: Effect on Therapeutic Decision Making in Patients with Potentially Resectable Brain Tumors[1]

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Purpose: To prospectively evaluate the effect of preoperative functional magnetic resonance (MR) imaging localization of language and motor areas on therapeutic decision making in patients with potentially resectable brain tumors.

Materials and Methods: The Institutional Review Board approved this HIPAA-compliant study, and each patient gave written informed consent. Thirty-nine consecutive patients (19 male, 20 female; mean age, 42.2 years) referred for functional MR imaging for possible tumor resection were prospectively evaluated. A preoperative diagnosis of brain tumor was made in all patients. Sentence completion and bilateral hand squeeze tasks were used to map language and sensory motor areas. Neurosurgeons completed questionnaires regarding the proposed treatment plan before and after functional MR imaging and after surgery. They also gave confidence ratings for functional MR imaging results and estimated the effect on surgical time, extent of resection, and surgical approach. The effect of functional MR imaging on changes in treatment plan was assessed with the Wilcoxon signed rank test. Differences in confidence ratings between altered and unaltered treatment plans were assessed with the Mann-Whitney *U* test. The estimated influence of functional MR imaging on surgical time, extent of resection, and surgical approach was denoted with summary statistics.

Results: Treatment plans before and after functional MR imaging differed in 19 patients ($P < .05$), with a more aggressive approach recommended after imaging in 18 patients. There were no significant differences in confidence ratings for functional MR imaging between altered and unaltered plans. Functional MR imaging resulted in reduced surgical time (estimated reduction, 15–60 minutes) in 22 patients who underwent surgery, a more aggressive resection in six, and a smaller craniotomy in two.

Conclusion: Functional MR imaging enables the selection of a more aggressive therapeutic approach than might otherwise be considered because of functional risk. In certain patients, surgical time may be shortened, the extent of resection increased, and craniotomy size decreased.

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Functional magnetic resonance (MR) imaging has shown tremendous potential as a noninvasive tool for preoperative planning by combining anatomic definition with physiologic information to demonstrate the spatial relationship between functionally eloquent brain regions and intracranial pathologic features (1–6). Functional MR imaging can be used to identify eloquent cortical regions (7,8), particularly when these cortical regions are displaced or reorganized secondary to pathologic processes (7,9–11), and can facilitate the assessment of potential neurosurgical risks (12).

In addition to providing information regarding the feasibility of resection, functional MR imaging may provide additional information regarding surgical approach and the selection of patients for invasive functional mapping (1). The results of numerous studies have shown agreement between functional MR imaging localization of sensory motor function and localization by means of invasive neurosurgical methods (13–15). Functional MR imaging has been shown to have high sensitivity (81%–92%) for the mapping of language areas in comparison with intraoperative electrocortical stimulation (16) and generates highly reproducible results for global and regional language lateralization, particularly in patients with epilepsy (17).

Despite demonstration of the technical and diagnostic efficacy of functional MR imaging compared with more invasive reference standards, definitive evidence that functional MR imaging substantially affects therapeutic decision making and patient outcome has not been fully established. Consequently, functional MR imaging has not been fully integrated into the broader clinical practice of neuroradiology. Thus, the purpose of our study was to prospectively evaluate the effect of preoperative functional MR imaging localization of language and motor areas on therapeutic decision making in patients with potentially resectable brain tumors.

Advances in Knowledge

- Functional MR imaging has a significant effect on therapeutic planning in patients with potentially resectable brain tumors by facilitating the selection of therapeutic options that might otherwise not have been considered because of functional risk.
- In certain patients, surgical time may be shortened, the extent of resection may be increased, and craniotomy size may be decreased.

Materials and Methods

Patients

The study protocol was approved by the hospital Institutional Review Board. Each patient gave written informed consent prior to participating in the study. The study was conducted with compliance to the Health Insurance Portability and Accountability Act. All patients were referred for preoperative functional MR imaging by three neurosurgeons (A.H.F., T.M.G., J.H.S.) at our institution between May 2004 and February 2005. Thirty-nine consecutive patients (19 male and 20 female patients; mean age, 42.2 years ± 18.2 [standard deviation]) with potentially resectable brain tumors were evaluated prospectively (Table 1).

Imaging

All imaging was performed by using a 1.5-T MR imager (Horizon; GE Medical Systems, Milwaukee, Wis) equipped with echo-planar imaging capabilities. A three-plane localizer image was initially obtained to identify anatomic landmarks and to allow positioning of the transverse sections parallel to the anterior commissure–posterior commissure line. Functional MR imaging of the brain was performed during sentence completion and bilateral hand squeeze tasks by using T2*-weighted blood oxygen level—dependent MR imaging (2000/40 [repetition time msec/echo time msec], 24 × 24-cm field of view, 64 × 64 matrix, 5-mm section thickness, and no intersection gap), and anatomic imaging was performed at the same section position by using dual-echo long-repetition-time spin-echo MR imaging (3000/14/84 [repetition time msec/echo time msec/inversion time msec], 24 × 24-cm field of view, 256 × 192 matrix, 5-mm section thickness, no intersection gap, and echo train length of eight).

Paradigm

All paradigms were controlled by using the CIGal software program (developed by J.T.V. [18]) operating on a Windows XP platform (Microsoft, Redmond, Wash). The software provided real-time video and audio stimulus presentation, behavioral response monitoring, and accurate synchronization with the MR imager. For language tasks, patients were shown sentences with blanks and were asked to silently fill in the blanks. For example, "The American flag is red, white and _____." This was followed by the control condition for which patients were shown scrambled letters parsed into groups to simulate the appearance of text and were instructed to guide their eyes over the pseudo-text. The following is an example of the pseudo-text used for the control condition: "Mry Ghtpieuw ghyr mo ywu, qoiem chg _____." The tasks and control conditions were matched for sentence length. Patients were also asked to perform a motor task that involved alternating hand squeezing. Both of these tasks (language and motor tasks) have been shown to induce reliable activation in language areas (16,19) and hand

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sensory motor areas (20,21). All patients were trained in verbal and motor tasks 10 minutes prior to examination. Stimuli were projected onto a translucent screen that was positioned alongside the MR imager. Stimuli were viewed by way of a mirror that was mounted on the head coil.

There were no failures due to technical difficulties or to an inability to perform tasks or obtain usable data. The time involved in performing an entire preoperative functional MR imaging session, which included complete patient training and the acquisition of structural images, was less than 1 hour, with approximately 30 minutes for actual imaging.

Image Analysis

Functional MR imaging data were analyzed by using the fScan image analysis program (developed by J.T.V. [18,22]), and *t* test activation maps were generated to reveal the degree to which variations in MR signal intensity corresponded to fluctuations in task stimulus and performance. These voxel-wise assays were created in real time, which enabled immediate identification of imaging problems and interactive determination of when enough data had been collected to produce adequate mapping results (J.T.V., 10 years of experience in functional MR imaging). Maps were convolved with a 10-mm smoothing kernel and were thresholded to a *t* value, which varied from 1.5 to 3.0 depending on the threshold for optimal localization of the activation foci. Statistical data were overlaid in color on a registered set of coplanar conventional dual-echo long-repetition-time spin-echo MR images.

Image Interpretation

Images were reviewed in consensus by two neuroradiologists (J.R.P. and L.M.S., with 10 years and 1 year of experience in functional MR imaging, respectively) who rendered a written interpretation. This interpretation consisted of an annotated set of T2-weighted MR images with thresholded activation maps superimposed as a color-coded overlay. The report included the identification of active areas, the presumed function that the active areas corresponded to, and the proximity of these areas to the tumor.

Effect of Assessment on Treatment Plan

The referring neurosurgeons were given questionnaires regarding their treatment plan before and after receiving the functional MR imaging interpretation. The preoperative questionnaire, which was given to neurosurgeons before functional MR imaging, included questions regarding the indication for functional MR imaging, the preoperative treatment plan, and additional diagnostic testing (eg, Wada testing) that would be performed if functional MR imaging were not available. Plan options, which were listed in order of increasingly aggressive therapy and

Table 1

Patient Demographics

Patient No./Sex/Age (y)	Diagnosis	Hemisphere
1/M/76	Glioblastoma multiforme	Left temporal
2/M/69	Glioblastoma multiforme	Left temporal
3/F/44	Glioblastoma multiforme	Left parietooccipital
4/F/27	Anaplastic astrocytoma	Left frontotemporal
5/F/20	Pleomorphic xanthoastrocytoma	Left temporooccipital
6/F/38	Anaplastic astrocytoma	Left parietal
7/M/70	Glioblastoma multiforme	Left parietal
8/F/49	Glioblastoma multiforme	Left frontal
9/M/56	Glioblastoma multiforme	Left temporal
10/F/31	Glioblastoma multiforme	Left frontal
11/M/53	Glioblastoma multiforme	Left parietooccipital
12/F/23	Central neurocytoma	Left intraventricular
13/M/77	Metastatic adenocarcinoma	Left temporal
14/M/44	Anaplastic oligodroglioma	Left frontoparietal
15/F/66	Anaplastic oligodroglioma	Left frontal
16/M/30	Well-differentiated astrocytoma	Left frontal
17/M/44	Well-differentiated astrocytoma	Left frontal
18/M/53	Malignant primitive neuroectodermal tumor with gliosarcomatous and neuroblastic elements	Left temporal
19/F/49	Glioblastoma multiforme	Right frontal
20/M/26	Glioblastoma multiforme	Left frontotemporal
21/M/26	Gliosis	Left temporal
22/M/37	Glioblastoma multiforme	Right frontal
23/F/44	Glioblastoma multiforme	Left temporoparietal
24/F/64	Glioblastoma multiforme	Right posterior frontal and parietal
25/F/33	Glioblastoma multiforme	Left frontal
26/M/43	Glioblastoma multiforme	Left frontal
27/M/52	Oligodendroglioma	Left frontal
28/M/60	High-grade glioma	Right frontal
29/M/57	Glioblastoma multiforme	Left frontal and temporal
30/F/72	Epidermoid	Left frontotemporal
31/F/27	Anaplastic oligoastrocytoma	Right parietal
32/M/69	Glioblastoma multiforme	Left temporal
33/F/45	Giant cell glioblastoma multiforme	Right posterior frontal
34/F/27	Well-differentiated astrocytoma	Left frontoparietal
35/F/54	Meningioma	Right frontal
36/F/31	Anaplastic glioma	Left temporal
37/M/8	Well-differentiated oligodendroglioma	Right posterior frontal
38/F/16	Ganglioglioma	Left occipital
39/F/15	Simple cyst and gliosis	Right temporal

surgical risk, included *(a)* no surgery, *(b)* biopsy, *(c)* craniotomy with intraoperative cortical mapping, performed with sedation, and *(d)* craniotomy without mapping, performed with a general anesthetic.

The functional MR imaging questionnaire, which was given to neurosurgeons after functional MR imaging, included questions regarding the preoperative plan after taking into account the functional MR imaging results. The neurosurgeons were asked to rate on a scale of 1–5 their confidence in the functional MR imaging results for the lateralization and 1 localization of expressive speech, receptive speech, and motor function (0, no confidence in results; 1, results suggestive of lateralization; 2, results could be used as a rough guide to surgical planning; 3, lateralization and localization are likely but need confirmation; 4, fairly confident in results; and 5, very confident in results).

A postoperative questionnaire was used in patients who underwent surgery to establish the type of surgical procedure that was actually used (plan options *b*–*d*) and to determine how (if at all) functional MR imaging affected surgical time, the extent of surgical resection, and surgical approach.

Table 2

Effect of Functional MR Imaging on Therapeutic Decision Making

Treatment Plan before Functional MR Imaging	Treatment Plan after Functional MR Imaging*: No Surgery	Biopsy	Craniotomy with Intraoperative Mapping	Craniotomy with General Anesthesia
No surgery	2	2	5	0
Biopsy	0	0	7	1
Craniotomy without sedation	0	1	13	3
Craniotomy with sedation	0	0	0	5

* Actual intervention agreed with treatment plan after functional MR imaging in all 39 patients.

Figure 1

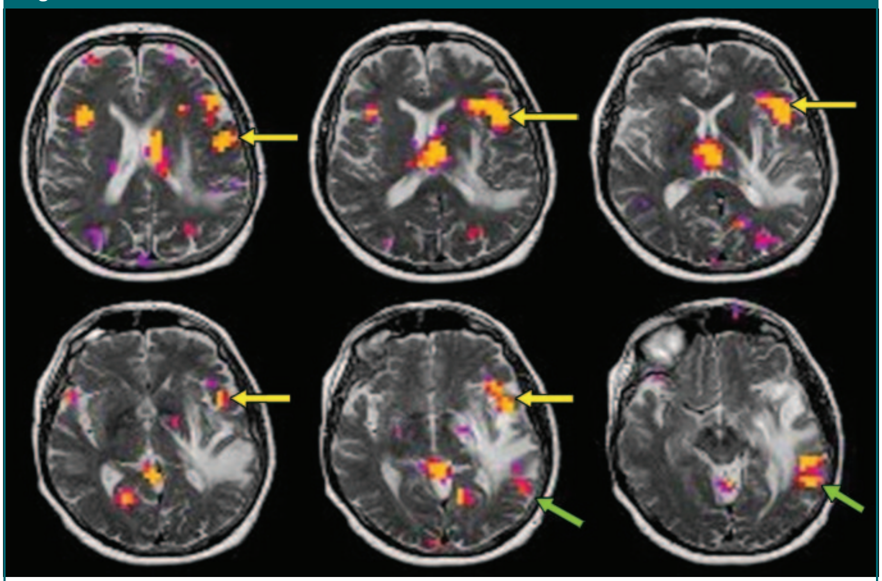

Figure 1: Left temporal lobe metastatic adenocarcinoma in 77-year-old man. Transverse functional MR images derived from series of T2*-weighted echo-planar MR images (2000/40, 24 × 24-cm field of view, 64 × 64 matrix, 5-mm section thickness, no intersection gap) are displayed as thresholded activation maps overlaid in red and yellow on a set of coplanar transverse T2-weighted fast spin-echo MR images (3000/84, 24 × 24-cm field of view, 256 × 192 matrix, 5-mm section thickness, no intersection gap, echo train length of eight). Surgery was not initially planned because of presumed involvement of receptive speech area. Left inferior frontal gyral activation (yellow arrows) is consistent with dominant expressive speech area and is separate from but abuts anterior margin of superior aspect of T2-weighted signal intensity abnormality in left temporal lobe and superior aspect of small left frontal T2 component. Left middle temporal gyrus activation (green arrows) is consistent with dominant receptive speech area and is lateral to midposterior portion of T2 hyperintense component. Craniotomy with mapping was performed, and resection was extended. No postoperative neurologic deficits were documented.

Statistical Analysis

A Wilcoxon signed rank test was used to assess any significant changes between treatment planning before and after functional MR imaging, equally weighting incremental changes in the plan ranked on a scale of 1–4 from least to most aggressive. Differences in confidence regarding the functional MR imaging result for lateralization of speech and localization of speech and motor function, between patients in whom the therapeutic plan was altered and those in whom it was not altered, were assessed by using the Mann-Whitney *U* test. The estimated influence of functional MR imaging on surgical time, extent of resection, and surgical approach was denoted with summary statistics. Statistical tests were performed by using a commercially available software program (SPSS, version 12.2; SPSS, Chicago, Ill), and a *P* value of .05 was considered to indicate a statistically significant difference. Trends in the estimated reduction in surgical time over the course of the study were assessed graphically in 3-month intervals.

Results

Effect on Treatment Plan

Functional MR imaging significantly altered (Table 2) the neurosurgeon's therapeutic plan in 19 (49%; 95% confidence interval: 33.0%, 64.4%) of 39 patients and enabled a more aggressive approach in 18 patients (46%; 95% confidence interval: 30.5%, 61.8%) ($P < .001$). Of the nine patients in whom no surgical intervention was initially planned, five were changed to craniotomy with mapping, two were changed to biopsy, and two remained unchanged and did not undergo surgery (Figs 1, 2). Of the 30 patients who were scheduled to undergo surgical intervention, seven were changed from biopsy to craniotomy with mapping, one was changed from biopsy to craniotomy with general anesthesia, and three were changed from craniotomy with mapping to craniotomy with general anesthesia as a result of the functional MR imaging results (Figs 3–5).

Additional invasive diagnostic testing (eg, Wada testing) would have been requested in four of 30 patients but was avoided in all of these patients after functional MR imaging. In one patient, the neurosurgeon altered the treatment plan to a less aggressive surgical approach after functional MR imaging. This patient experienced progressive hemiplegia preoperatively and, because functional MR imaging showed encasement of the motor area by the lesion in the precentral gyrus, the treatment plan was changed from craniotomy with mapping to biopsy (Fig 6).

Confidence Ratings

The median confidence rating was 4 for the localization of speech and motor function and 5 for the lateralization of speech function. Median confidence ratings for functional MR imaging did not differ significantly ($P < .05$) between patients in whom the treatment plan was altered and those in whom it was not altered.

Surgical Time, Resection, and Approach

In addition to the surgical treatment plan, functional MR imaging also affected surgical time, the extent of surgical resection, and surgical approach, as determined by means of the postoperative questionnaire. By facilitating the localization of motor and language areas, functional MR imaging helped to shorten surgical time by an estimated 15–60 minutes in 22 (60%; 95% confidence interval: 43.6%, 75.3%) of 37 patients. There was an increasing trend in this regard for the first three quarters of the study (Fig 7). In six (16%; 95% confidence interval: 4.3%, 28.1%) of 37 patients who underwent surgery, the neurosurgeon specifically commented that the functional MR imaging results enabled a more complete resection than otherwise would have been achieved. Surgical approach was also affected, with a smaller craniotomy performed in two (5%; 95% confidence interval: 1.9%, 12.7%) of 37 patients.

Figure 2

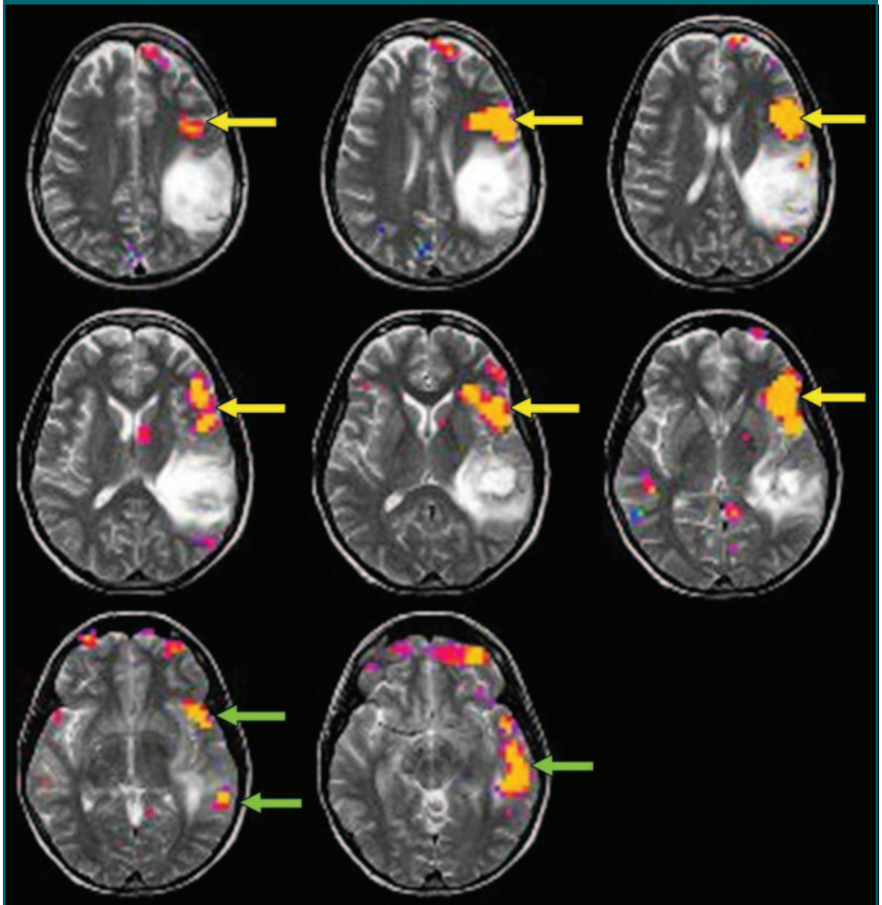

Figure 2: Recurrent left parietal lobe anaplastic astrocytoma in 37-year-old right-handed woman. Transverse functional MR images derived from series of T2*-weighted echo-planar MR images (2000/40, 24 × 24-cm field of view, 64 × 64 matrix, 5-mm section thickness, no intersection gap) are displayed as thresholded activation maps overlaid in red and yellow on a set of coplanar transverse T2-weighted fast spin-echo MR images (3000/84, 24 × 24-cm field of view, 256 × 192 matrix, 5-mm section thickness, no intersection gap, echo train length of eight). Surgery was not initially planned because of presumed involvement of receptive speech area. Left inferior and middle frontal gyral activation (yellow arrows) is consistent with dominant expressive speech area and is located at anterior border of more cephalad component of lesion. Left superior and middle temporal gyral activation (green arrows) is consistent with dominant receptive speech area and abuts inferior border of temporal component of lesion, with superior temporal gyral activation component lying anteroinferior to lesion. Biopsy was performed, and no postoperative neurologic deficits were documented.

Discussion

The results of our study indicate that functional MR imaging has a significant effect on therapeutic planning in patients with potentially resectable brain tumors by altering the treatment plan—most often to a more aggressive approach—in a significant number of patients. In certain patients, surgical time may be shortened, the extent of resection may be larger, and the craniotomy size may be smaller. Additional invasive diagnostic testing (eg, Wada testing) would otherwise have been performed in a few of the patients but was avoided by using functional MR imaging.

For patients in whom the treatment plan was not altered, functional MR imaging likely contributed confidence to the neurosurgeons' decision to proceed with the planned treatment approach. The neurosurgeons' confidence ratings for these patients were not significantly different from those for patients in whom the treatment plan was altered. Of note, there were two patients in whom the preoperative plan of no surgery was confirmed by means of functional MR imaging.

Studies in the literature corroborate the lack of postoperative neurologic deficits in patients who have undergone preoperative functional MR imaging (11,23). The influence of functional MR imaging on therapy has also been suggested in the literature (13). In the study by Wilkinson et al (11) it was shown that, when functional MR imaging data were incorporated into neuronavigation-guided surgical approaches, functional MR imaging facilitated safe tumor resection in anatomic areas that were previously thought to be high risk, without intraoperative cortical mapping, by means of conventional MR imaging. In a retrospective study, Lee et al (1) demonstrated that functional MR imaging was complementary to invasive functional mapping. The effect of functional MR imaging on therapeutic planning has been documented thus far in only one prospective study in which investigators demonstrated considerable influence on diagnostic and therapeutic decision making in patients with epilepsy (24).

Figure 3

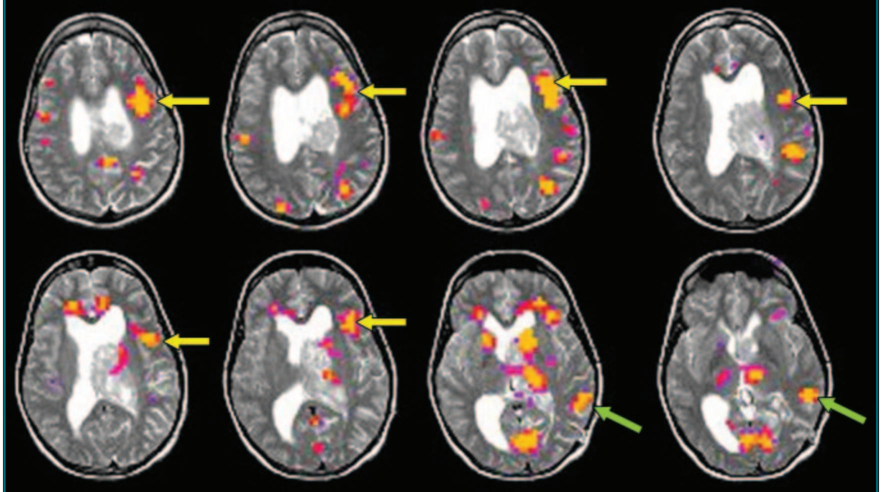

Figure 3: Left intraventricular central neurocytoma in 23-year-old left-handed woman. Transverse functional MR images derived from series of T2*-weighted echo-planar MR images (2000/40, 24 × 24-cm field of view, 64 × 64 matrix, 5-mm section thickness, no intersection gap) are displayed as thresholded activation maps overlaid in red and yellow on a set of coplanar transverse T2-weighted fast spin-echo MR images (3000/84, 24 × 24-cm field of view, 256 × 192 matrix, 5-mm section thickness, no intersection gap, echo train length of eight). Preoperative plan included Wada testing and possible craniotomy with mapping. Dominant expressive speech area is shown in left middle and inferior frontal gyri (yellow arrows) and is anterolateral to lateral ventricular component of lesion. Left superior and middle temporal gyral activation (green arrows) is consistent with dominant receptive speech area and is anterior and inferolateral to left atrial component of lesion. Imaging results confirmed left dominant speech; Wada testing was avoided. Lesion was resected during craniotomy with general anesthesia by using right paramedian approach. No postoperative neurologic deficits were documented.

Despite the increasing clinical use of functional MR imaging as a preoperative planning tool, there are several limiting factors that are intrinsic to the method itself. First, functional MR imaging is an indirect activation modality that shows some (but not necessarily all) of the brain areas that participate in the execution of a particular task. In particular, functional MR imaging cannot differentiate between activation in brain areas that are simply correlated with a particular function and activation in brain areas that are truly essential for performing that function. Second, the pathologic features of tissue can alter signal intensity on blood oxygen level–dependent functional MR images in a manner that has not been fully characterized (25,26). Third, accuracy in mapping the spatial extent of the activated voxels is limited and depends on the statistical threshold chosen. Individuals vary in their functional MR activation levels for a given task. Fitzgerald et al (16) described variable activation in individuals across a variety of task paradigms in many brain regions. Finally, functional MR imaging requires active participation by a cooperative patient, a condition that is not always feasible in the neuro-oncologic population.

There are multiple steps that can be taken to reduce the effect of these limitations. In our study, we used a standardized imaging and analysis protocol, consistent neuroradiologists, and a small group of neurosurgeons to minimize the variability in methods across the patient population. Variations in the pathologic characteristics of the tumors, the perceived tumor extent, and the surrounding edema may account for some of the variability in the neurosurgeons' confidence in the accuracy of the spatial extent of localization.

To minimize task performance variability across different patients, we used real-time functional MR imaging analysis and head-motion plots to allow the operator to assess the quality of the data at the time of imaging. The operator views functional MR imaging activation maps and motion plots in real time and can assess an active area and plot fluctuations of task-related blood oxygen level–dependent signal intensity over time. In this way, head motion or task performance problems can be quickly identified and corrected so that new activation maps can be generated. In rendering a clinical interpretation for functional MR imaging, the neuroradiologist uses the combination of activation maps, activation time course plots, and expected anatomic location of functional areas.

Given that the small number of neurosurgeons who referred patients already had some confidence in functional MR imaging, another limitation of our study is referral bias, and the patients who were referred were those for whom the localization of eloquent speech and sensorimotor cortex might affect treatment planning. This approach, however, has an advantage in that, because it is used in clinical practice, it provides a realistic assessment of therapeutic options and the role of diagnostic functional MR imaging. Because the referring neurosurgeon also completed the preoperative, functional MR imaging, and postoperative questionnaires, this prospective study focused on the treatment effect of functional MR imaging for patients in whom functional MR imaging might be ordered, without attempting to assess its role across the entire population of potential patients.

Our study has addressed the issue of therapeutic planning effect without attempting to assess the patient outcome effect of functional MR imaging (27). For the latter, one would need to perform a randomized trial with a control population in whom functional MR imaging information was requested but not provided. To do so, however, would have ethical implications.

Because of rapid technologic advancements in medicine—particularly in the specialty of radiology—it is often difficult to establish the actual benefits of new techniques with a traditional hierarchical scientific assessment, which can take a relatively long period of time compared with the rapid evolution of new technology. Thus, new technologies are often implemented on the basis of subjective expectations of usefulness and/or experience with a limited number of patients (28). In fact, it has been suggested that all that may be needed to decide to implement a new technology is to demonstrate that the new diagnostic strategy facilitates clinical decision making without detriment to patient care (28). The goal of our study therefore was to establish if and how this new modality (ie, functional MR imaging) would affect therapeutic planning in the routine clinical environment.

Because it can be fully implemented in a busy clinical environment, functional MR imaging has a broad role in neurosurgical planning, including patient selection, assessment of the feasibility of surgery, and surgical planning. In the appropriate setting, it can be easily added to conventional MR imaging because of the speed of the study. Functional MR imaging can take less than 10 minutes to complete, which includes the time needed to perform online statistical analysis (29). This immediate feedback allows the radiologist to decide whether a given task needs to be repeated to ensure that the appropriate functional area is localized. We were successful in our study in patients with varying clinical functional status. There were no failures due to technical difficulties or to an inability to perform tasks or obtain usable data. The time involved in performing an entire preoperative functional MR imaging session,

Figure 4

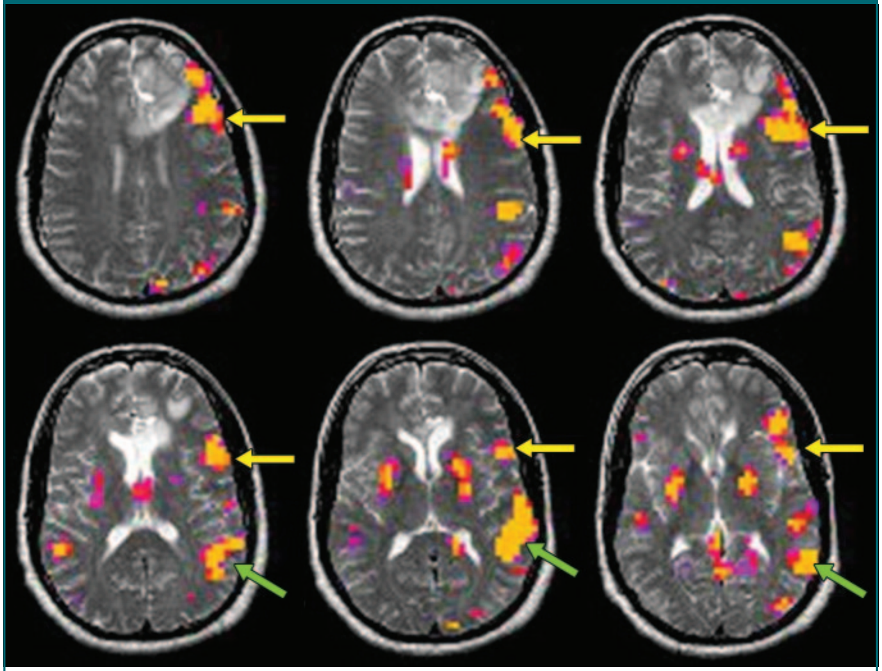

Figure 4: Medial left frontal lobe well-differentiated astrocytoma in 30-year-old man. Transverse functional MR images derived from series of T2*-weighted echo-planar MR images (2000/40, 24 × 24-m field of view, 64 × 64 matrix, 5-m section thickness, no intersection gap) are displayed as thresholded activation maps overlaid in red and yellow on a set of coplanar transverse T2-weighted fast spin-echo MR images (3000/84, 24 × 24-cm field of view, 256 × 192 matrix, 5-mm section thickness, no intersection gap, echo train length of eight). Craniotomy with general anesthesia was planned, with lesion presumed to be sufficiently removed from expressive speech areas. Left inferior frontal gyral activation (yellow arrows) is consistent with dominant expressive speech area located 1 cm inferolateral to posterior margin of left frontal lobe lesion. Left superior and middle temporal gyral activation (green arrows) is consistent with dominant receptive speech area, is located inferiorly, and is separated from left frontal lobe lesion by sylvian fissure. Imaging results helped confirm existing treatment plan. No postoperative neurologic deficits were documented.

Radiology

Figure 5

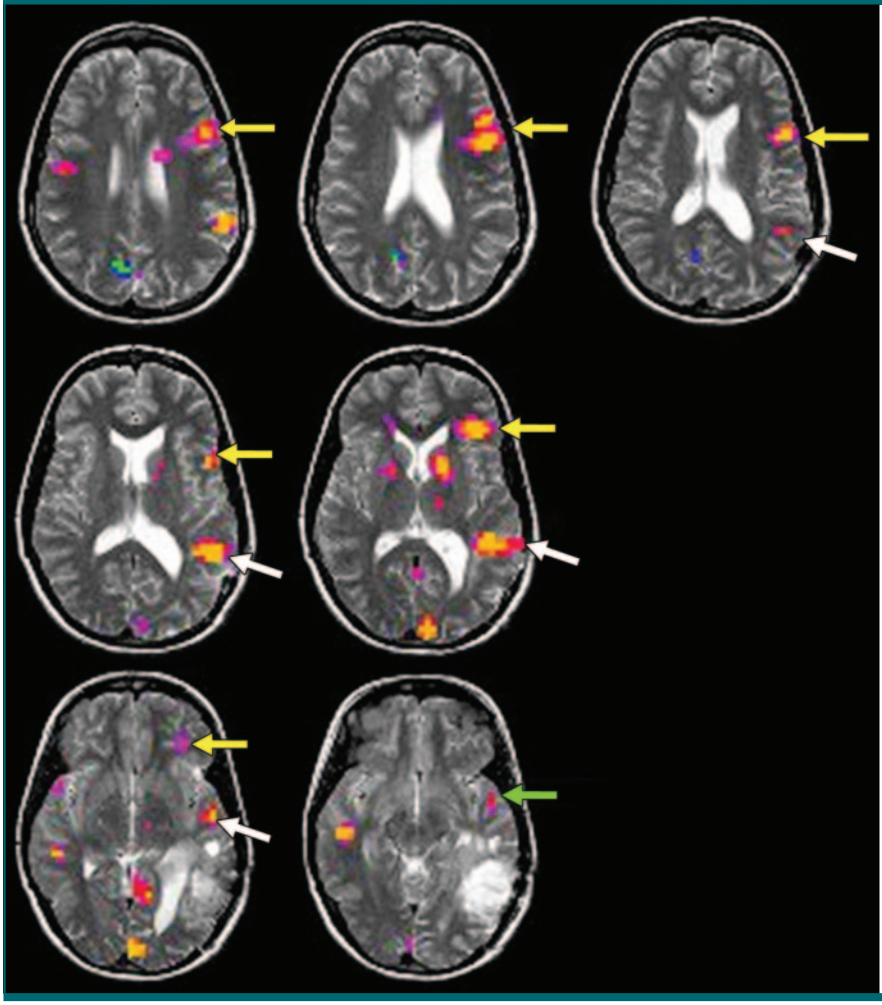

Figure 5: Left posterior temporooccipital region pleomorphic xanthoastrocytoma with anaplastic features in 20-year-old woman. Transverse functional MR images derived from series of T2*-weighted echo-planar MR images (2000/40, 24 × 24-cm field of view, 64 × 64 matrix, 5-mm section thickness, no intersection gap) are displayed as thresholded activation maps overlaid in red and yellow on a set of coplanar transverse T2-weighted fast spin-echo MR images (3000/84, 24 × 24-cm field of view, 256 × 192 matrix, 5-mm section thickness, no intersection gap, echo train length of eight). Biopsy was planned because of lesion proximity to presumed receptive speech area. Left inferior frontal gyral activation (yellow arrows) is consistent with expressive speech area. Left superior temporal gyrus activation (white arrows) is consistent with dominant receptive speech area and is anterior and superior to left temporooccipital resection cavity, with small component (green arrow) within 1 cm anterior to T2 signal intensity abnormality at superior aspect of resection cavity. Imaging results helped plan surgical approach, and craniotomy with mapping and resection were performed. No postoperative neurologic deficits were documented.

Figure 6

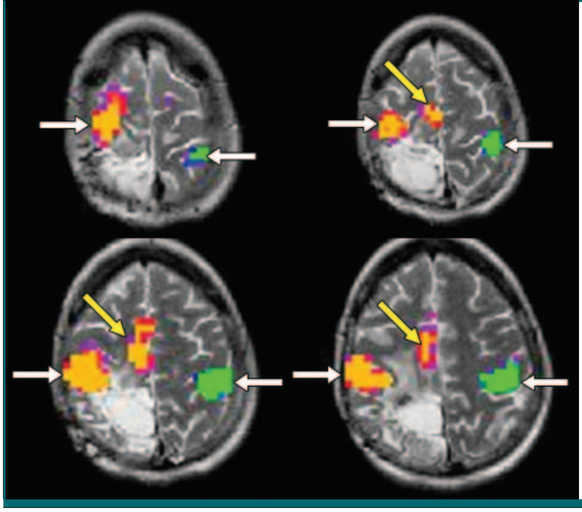

Figure 6: Right parietal lobe anaplastic oligodendroglioma in 23-year-old woman. Transverse functional MR images derived from series of T2*-weighted echo-planar MR images (2000/40, 24 × 24-cm field of view, 64 × 64 matrix, 5-mm section thickness, no intersection gap) are displayed as thresholded activation maps overlaid in red and yellow on a set of coplanar transverse T2-weighted fast spin-echo MR images (3000/84, 24 × 24-cm field of view, 256 × 192 matrix, 5-mm section thickness, no intersection gap, echo train length of eight). Resection and craniotomy with mapping were initially planned. Left-hand sensory motor area (yellow-red regions) is adjacent to anterior margin of superior portion of lesion in right parietal lobe. Bilateral sensory motor areas (white arrows) are shown, and activation is seen in supplementary motor cortex (yellow arrows). Because patient experienced left hemiplegia and because functional motor area was intimately involved with lesion, treatment plan was changed to biopsy. No postoperative neurologic deficits were documented.

Figure 7

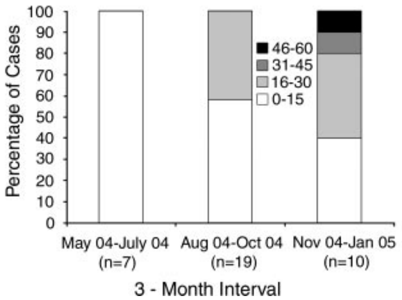

Figure 7: Bar graph illustrates trend for reduced surgical time (in minutes) over course of study between May 2004 and January 2005, presumably because of increased confidence in functional MR imaging. Patients who underwent surgery are indicated for each time period. Note that the study was terminated in February 2005, during which one additional patient (not shown) was included. This patient had an estimated reduction in surgical time of 0–15 minutes.

complete with structural image acquisition, was less than 1 hour, with approximately 10 minutes prior to the study for instruction on the tasks and approximately 30 minutes for actual imaging.

Future studies focusing on the outcome of patients who undergo preoperative functional MR imaging are still needed, though such studies will be difficult to perform. A randomized controlled trial in a large number of patients will be needed to show an effect because of the indirect relationship between the diagnostic test and patient outcome. Other issues warranting investigation include disease-specific effects on the measured blood oxygen level–dependent response, effects of individual variations in cerebrovascular anatomy, and effects due to the presence of incidental pathologic abnormalities (eg, atherosclerotic disease).

In conclusion, functional MR imaging has a significant effect on therapeutic planning in patients with potentially resectable brain tumors and enables the selection of therapeutic options that might otherwise not have been considered because of functional risk. In certain patients, surgical time may be shortened, the extent of resection may be larger, and craniotomy size may be smaller.

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References

1. Lee CC, Ward HA, Sharbrough FW, et al. Assessment of functional MR imaging in neurosurgical planning. AJNR Am J Neuroradiol 1999;20(8):1511–1519.
2. Krings T, Schreckenberger M, Rohde V, et al. Metabolic and electrophysiological validation of functional MRI. J Neurol Neurosurg Psychiatry 2001;71(6):762–771.
3. Tomczak RJ, Wunderlich AP, Wang Y, et al. fMRI for preoperative neurosurgical mapping of motor cortex and language in a clinical setting. J Comput Assist Tomogr 2000; 24(6):927–934.
4. Nitschke MF, Melchert UH, Hahn C, et al. Preoperative functional magnetic resonance imaging (fMRI) of the motor system in patients with tumours in the parietal lobe. Acta Neurochir (Wien) 1998;140(12): 1223–1229.
5. Roux FE, Boulanouar K, Ranjeva JP, et al. Cortical intraoperative stimulation in brain tumors as a tool to evaluate spatial data from motor functional MRI. Invest Radiol 1999; 34(3):225–229.
6. Cosgrove GR, Buchbinder BR, Jiang H. Functional magnetic resonance imaging for intracranial navigation. Neurosurg Clin N Am 1996;7(2):313–322.
7. Cravo I, Palma T, Conceicao C, Evangelista P. Preoperative applications of cortical mapping with functional magnetic resonance. Acta Med Port 2001;14(1):21–25.
8. Krings T, Schreckenberger M, Rohde V, et al. Functional MRI and 18F FDG-positron emission tomography for presurgical planning: comparison with electrical cortical stimulation. Acta Neurochir (Wien) 2002;144(9): 889–899.
9. Fandino J, Kollias SS, Wieser HG, Valavanis A, Yonekawa Y. Intraoperative validation of functional magnetic resonance imaging and cortical reorganization patterns in patients with brain tumors involving the primary motor cortex. J Neurosurg 1999;91(2):238–250.
10. Roux FE, Boulanouar K, Ibarrola D, Tremoulet M, Chollet F, Berry I. Functional MRI and intraoperative brain mapping to evaluate brain plasticity in patients with brain tumors and hemiparesis. J Neurol Neurosurg Psychiatry 2000;69(4):453–463.
11. Wilkinson ID, Romanowski CA, Jellinek DA, Morris J, Griffiths PD. Motor functional MRI for pre-operative and intraoperative neurosurgical guidance. Br J Radiol 2003;76(902): 98–103.
12. Haberg A, Kvistad KA, Unsgard G, Haraldseth O. Preoperative blood oxygen level-dependent functional magnetic resonance imaging in patients with primary brain tumors: clinical application and outcome. Neurosurgery 2004;54(4):902–915.
13. Jack CR Jr, Thompson RM, Butts RK, et al. Sensory motor cortex: correlation of presurgical mapping with functional MR imaging and invasive cortical mapping. Radiology 1994;190(1):85–92.
14. Puce A, Constable RT, Luby ML, et al. Functional magnetic resonance imaging of sensory and motor cortex: comparison with electrophysiological localization. J Neurosurg 1995;83(2):262–270.
15. Morioka T, Yamamoto T, Mizushima A, et al. Comparison of magnetoencephalography, functional MRI, and motor evoked potentials in the localization of the sensory-motor cortex. Neurol Res 1995;17(5):361–367.
16. Fitzgerald DB, Cosgrove GR, Ronner S, et al. Location of language in the cortex: a comparison between functional MR imaging and electrocortical stimulation. AJNR Am J Neuroradiol 1997;18(8):1529–1539.
17. Fernandez G, Specht K, Weis S, et al. Intrasubject reproducibility of presurgical language lateralization and mapping using fMRI. Neurology 2003;60:969–975.
18. Voyvodic JT. Real-time FMRI paradigm control, physiology, and behavior combined with near-real time statistical analysis. Neuroimage 1999;10(2):91–106.
19. Pouratian N, Bookheimer SY, Rex DE, Martin NA, Toga AW. Utility of preoperative functional magnetic resonance imaging for identifying language cortices in patients with vascular malformations. J Neurosurg 2002; 97(1):21–32.
20. Papke K, Hellmann T, Renger B, et al. Clinical applications of functional MRI at 1.0 T: motor and language studies in healthy subjects and patients. Eur Radiol 1999;9(2): 211–220.
21. Hirsch J, Ruge MI, Kim KH, et al. An integrated functional magnetic resonance imaging procedure for preoperative mapping of cortical areas associated with tactile, motor, language, and visual functions. Neurosurgery 2000;47(3):711–721.
22. Voyvodic JT. AMPLE (activation mapping as a percentage of local excitation) fMRI: stability within scans, between scans, and field strengths [abstract]. In: Proceedings of the 13th Meeting of the International Society for Magnetic Resonance in Medicine. Berkeley,

Calif: International Society for Magnetic Resonance in Medicine, 2003; 1595.

23. Holodny AI, Schulder M, Liu WC, Wolko J, Maldjian JA, Kalnin AJ. The effect of brain tumors on BOLD functional MR imaging activation in the adjacent motor cortex: implications for image-guided neurosurgery. AJNR Am J Neuroradiol 2000;21(8):1415–1422.

24. Medina LS, Bernal B, Dunoyer C, et al. Seizure disorders: functional MR imaging for diagnostic evaluation and surgical treatment—prospective study Radiology 2005; 236(1):247–253.

25. Holodny AI, Schulder M, Liu WC, Maldjian JA, Kalnin AJ. Decreased BOLD functional MR activation of the motor and sensory cortices adjacent to a glioblastoma multiforme: implications for image-guided neurosurgery. AJNR Am J Neuroradiol 1999;20(4):609–612.

26. Maldjian J, Atlas SW, Howard RS 2nd, et al. Functional magnetic resonance imaging of regional brain activity in patients with intracerebral arteriovenous malformations before surgical or endovascular therapy. J Neurosurg 1996;84(3):477–483.

27. Gazelle GS, McMahon PM, Siebert U, Beinfeld MT. Cost-effectiveness analysis in the assessment of diagnostic imaging technologies. Radiology 2005;235:361–370.

28. Hunink MG, Krestin GP. Study design for concurrent development, assessment, and implementation of new diagnostic imaging technology. Radiology 2002;222(3):604–614.

29. Frank JA, Ostuni JL, Yang Y, et al. Technical solution for an interactive functional MR imaging examination: application to a physiologic interview and the study of cerebral physiology. Radiology 1999;210(1): 260–268.