

Clinical study

Intraoperative magnetic resonance for the surgical treatment of lesions producing seizures

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Summary Seizures are a major presenting feature of several non-neoplastic cerebral lesions. We reviewed the experience at the Brigham and Women's Hospital, Boston, on the surgical management of benign intracerebral lesions presenting with seizures with intraoperative magnetic resonance imaging (iMRI) guidance. Our aim was to demonstrate that this is an effective and efficient treatment for these lesions. The histories of thirteen patients who presented with seizures secondary to benign intraaxial lesions treated by craniotomy and resection within the iMRI unit at our institution were reviewed. The surgical results, histology and clinical outcomes were reviewed. The mean follow-up was 22.1 months (range 2–48). In all cases, lesions were accurately located with iMRI. After initial macroscopic resection, 5 cases were found to have residual lesion. All had complete radiological resection at the end of the procedure. At follow-up, five patients had no seizures, 5 had rare seizures and the remaining 3 had worthwhile improvement in seizure frequency. Intraoperative MRI is a safe and effective adjunct for the surgical treatment of benign intracerebral lesions presenting with seizures. It provides effective and efficient intraoperative guidance for planning and approach to the lesion and the assurance that the lesion is totally removed. Surgical resection with iMRI may, therefore, provide a useful approach to these lesions. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: cortical dysplasia, dysembryoplastic neuroepithelial tumor, epilepsy, ganglioglioma, intraoperative MRI

INTRODUCTION

Intraoperative magnetic resonance imaging (iMRI) is becoming increasingly prevalent.^{1–5} Initial reports have been focused on biopsy or resection of malignant brain tumors^{4–6} but the scope and usefulness of iMRI appears to be much wider. In the approach to epilepsy, modern imaging techniques have been central to guiding effective surgical treatments.⁷ Amongst benign intraaxial tumors, gangliogliomas and dysembryoplastic neuroepithelial tumors (DNTs) are amongst the most common, often presenting with seizures.⁸ Cerebral hamartomas and cortical dysplasias may also be sources of epileptic foci.^{9,10}

It is becoming more obvious that very subtle abnormalities on MRI can correlate with definite pathology that act as epileptic foci.^{10,11} When considered together with EEG changes and seizure semiology, identification of abnormalities on MRI are major predictors of success in surgery,^{10,12} since resection of these lesions may be an effective treatment for these patients. More complete resection has a greater likelihood of improving epilepsy.¹⁰ Small and deep lesions often require image guidance for surgical accuracy. Framed and unframed stereotactic systems have been employed,¹³ however, both suffer from brain shift therefore limiting the overall clinical accuracy of these navigation methods.¹⁴ Intraoperative imaging allows for these changes, and since many of these lesions are seen best on MRI, iMRI would appear to be ideal for the surgical approach to these lesions. We report here the first

series of such patients treated within an iMRI unit as the primary image guidance system.

PATIENTS AND METHODS

Patient selection

There were 13 patients operated on for benign intraaxial lesions between 1996 and 2000 excluding patients with mesial temporal sclerosis. There were 7 males and 6 females. The mean age was 26.1 years (range 5–40). The mean length of symptoms was 54.8 months (range 6–180). All patients presented with seizures. The patient details are presented in Table 1.

Preoperative investigation and intraoperative magnetic resonance system

All patients had structural lesions identified on preoperative MRI scans, as well as surface EEG monitoring (ictal and interictal). Surface EEG analysis was consistent with the MRI-identified abnormality being the seizure focus in eleven cases. One patient (case 6) had prolonged video-EEG monitoring with surface and sphenoidal electrodes and later placement of subdural grids. One patient (case 13) suffered from gelastic seizures, which was consistent with the finding of a hypothalamic lesion on MRI. The latter was consistent with the presence of an occipital lobe focus, correlating with an abnormality seen on MRI. One patient (case 7) also had an interictal PET scan, which did not contribute significant information. Based on this data, in consultation with an epileptologist (EB) and neurosurgeon (PB), it was decided that the initial treatment should be an attempted excision of the structural lesion identified on MRI.

The iMRI suite has been well described in previous publications.^{1,5,15} Briefly, the prototype General Electric Signa SP open configuration iMRI scanner is a 'double-doughnut' design established within a fully equipped operating suite. The

Received 18 January 2002
Accepted 20 February 2002

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Table 1 Details of patients presented in this series. Outcome is according to the Engel classification

Patient Number	Age	Gender	Presentation	Previous surgery	Site	Pathology	Complications	Outcome
1	5	f	Refractory epilepsy		L occipital	DNET	none	II
2	37	f	Refractory epilepsy		R temporal	DNET	none	II
3	40	m	Refractory epilepsy		R temporal–mesial	DNET	DVT	I
4	39	m	Refractory epilepsy		R occipital	dysplasia	none	III
5	4	m	Refractory epilepsy		L frontal	dysplasia	none	III
6	39	m	Refractory epilepsy		R occipital	dysplasia	hemianopia	I
7	24	m	Single seizure, headache		R frontal	dysplasia	none	I
8	21	f	Single seizure		L temporal–mesial	ganglioglioma	none	III
9	18	f	Single seizure		R temporal	ganglioglioma	none	I
10	20	f	Single seizure		R temporal	ganglioglioma	none	III
11	29	m	Refractory epilepsy		R temporal	ganglioglioma	none	III
12	36	m	Single seizure, weakness		R parietal	ganglioglioma	none	I
13	27	f	Gelastic seizures	Yes	hypothalamus	hamartoma	none	III

standard GE Signa control console with software is used for image acquisition. All standard pulse sequences are available. Flexible coils are used to maximize patient access. Two slots on either side of the ‘doughnuts’ allow a surgeon and an assistant to perform all phases of the operation within the magnet. Images are displayed on screens located within the bore of the magnet.

A digital 3-D optical stereotactic system is incorporated into the bore of the magnet. This is also previously described.⁵ This device allows for the registration of instruments in space, which when attached to small light-emitting diodes within the surgical field, can be tracked by the integration of specially designed software on a Sun workstation.⁵ Since January 1999, we have used specially designed software, called the 3D Slicer software package.¹⁶ It has therefore been applied to 9 patients in the current series.

Patient procedures

With informed consent the decision was made to proceed with surgical excision of structural lesions. All procedures were performed within the iMRI unit at the Brigham and Women’s Hospital, Boston. All patients had craniotomies performed under general anesthetic. Patients were positioned on a padded couch in the supine or prone position, depending on the location of the lesion. A MRI-compatible Mayfield head clamp was used.

After positioning, a series of multislice (T1 and T2) images were acquired to assess the adequacy of positioning and to plan the approach. Often a surface marker visible on MRI images, such as a vitamin E tablet, was used during this phase. Once the appropriate skin incision was confirmed, the scalp was prepped and draped as previously described.⁵ A craniotomy was performed in the standard fashion.

After the dura was opened, imaging was repeated. Those image sequences that showed the lesion most effectively were then used for integration with the image guidance software. A probe was then attached to a handle with optical tracking sensors, enabling intraoperative frameless stereotactic guidance. As appropriate, corticotomy and resection of the lesion were performed, using the frameless stereotaxy to guide the approach. Macroscopic resection was performed in all cases. MRI imaging was then repeated to confirm total resection of the lesion. If abnormal tissue was still observed on these images, resection was continued. Total radiological resection was achieved in all cases.

Table 2 Pathological diagnosis of lesions excised

Pathology	Number
Ganglioglioma	5
Cortical dysplasia	4
Dysembryoplastic neuroepithelial tumor	3
Hamartoma	1

The dura was then closed in the usual fashion. Imaging was repeated at this stage to exclude the presence of an intracranial hematoma. The bone was replaced and fixed with titanium plates and the scalp was closed in layers.

RESULTS

Procedures performed and pathological diagnosis

Thirteen patients underwent craniotomy and resection of cerebral lesions for epilepsy. The goal in each case was to remove the lesion primarily and some perilesional tissue if this was safe to perform. In all cases, the scalp flaps were accurately positioned, as was the craniotomy. The lesions were all approached and found using the built-in image-guidance system and software without problems. After initial resection, residual lesion was identified in five patients, therefore leading to further resection. All had total radiological resection. The pathological diagnoses are summarized in Table 2.

There were no hemorrhagic or infective complications. One patient had a deep vein thrombosis. Two patients had temporary neurological worsening after resection. One patient (case 6) who underwent resection of a right occipital lesion, had a left homonymous hemianopia immediately postoperatively which had partially recovered 2 months postoperatively.

Clinical outcome

Follow-up for the patients in this series ranged from 2 to 48 months (mean 22.1). Seizure outcome was graded according to Engel et al.⁷ Five patients had no further seizures (four were not taking antiseizure medication; Engel Class I) (2 cortical dysplasias, 2 gangliogliomas, one DNT), 5 patients had rare seizures only (one was not taking antiseizure medication; Engel Class II) (3 gangliogliomas, 2 DNTs) and 3 had worthwhile improvement in seizure frequency (Engel Class III) (2 cortical dysplasias, 1 hamartoma).

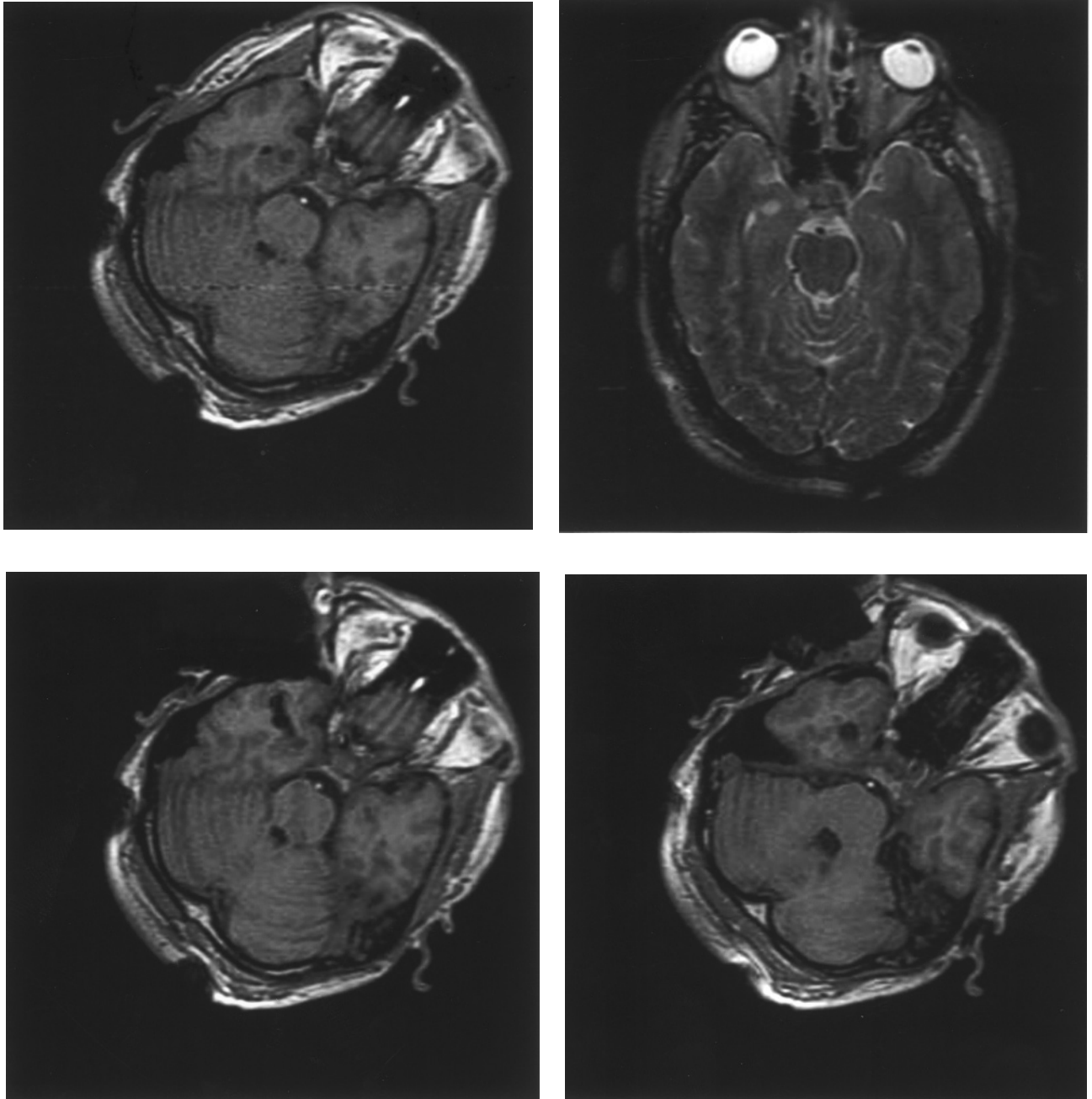


Fig. 1 Patient 3. Top Left. Axial SPGR iMRI image taken before actual surgery commenced, showing a well circumscribed hypodense lesion of the mesial right temporal lobe. Top Right. Axial T2 iMRI image taken before surgery. A routine set of images are taken before commencement of surgery to plan the surgical approach. Bottom Left. Axial SPGR iMRI image showing direct surgical approach to the lesion. Significant shift of the temporal lobe is observed. Bottom Right. Axial SPGR iMRI image after removal of the lesion, which was shown to be a DNT.

Case illustration: patient 3

This 40 year-old, right-handed male presented with a 6 month history of temporal lobe seizures. He had been commenced on phenytoin which reduced the frequency of seizures but did not eliminate them. An MRI scan was performed and this revealed a lesion which was 1.5cm in diameter in the medial right temporal lobe. It was hypointense on T1-weighted images and hyperintense on T2 images (Fig. 1). It showed minimal enhancement after gadolinium injection.

An interictal EEG was consistent with the presence of an epileptic focus in the right temporal lobe. A right temporal craniotomy was performed under general anesthetic. Using intraoperative imaging and guidance, the lesion was approached through the middle temporal gyrus. It was easily located using the 3-D slicer guidance system, despite significant brain

shift (Fig. 1, bottom left) and then macroscopically removed. Repeat imaging confirmed the total removal of the lesion (Fig. 1, bottom right). Histology was consistent with DNT.

Postoperatively, the patient did well with no neurological deficit. He was discharged from hospital on D4, but presented to a local hospital with a painful, swollen calf. A deep vein thrombosis was confirmed, and he was commenced on warfarin. At last follow-up (4 months postoperatively), he remained seizure free. He was continuing to take phenytoin at the time of review.

Case illustration: patient 8

This 21 year-old, right handed female had suffered from temporal lobe epilepsy for 3 years prior to surgery. She had poorly controlled seizures, despite treatment with various

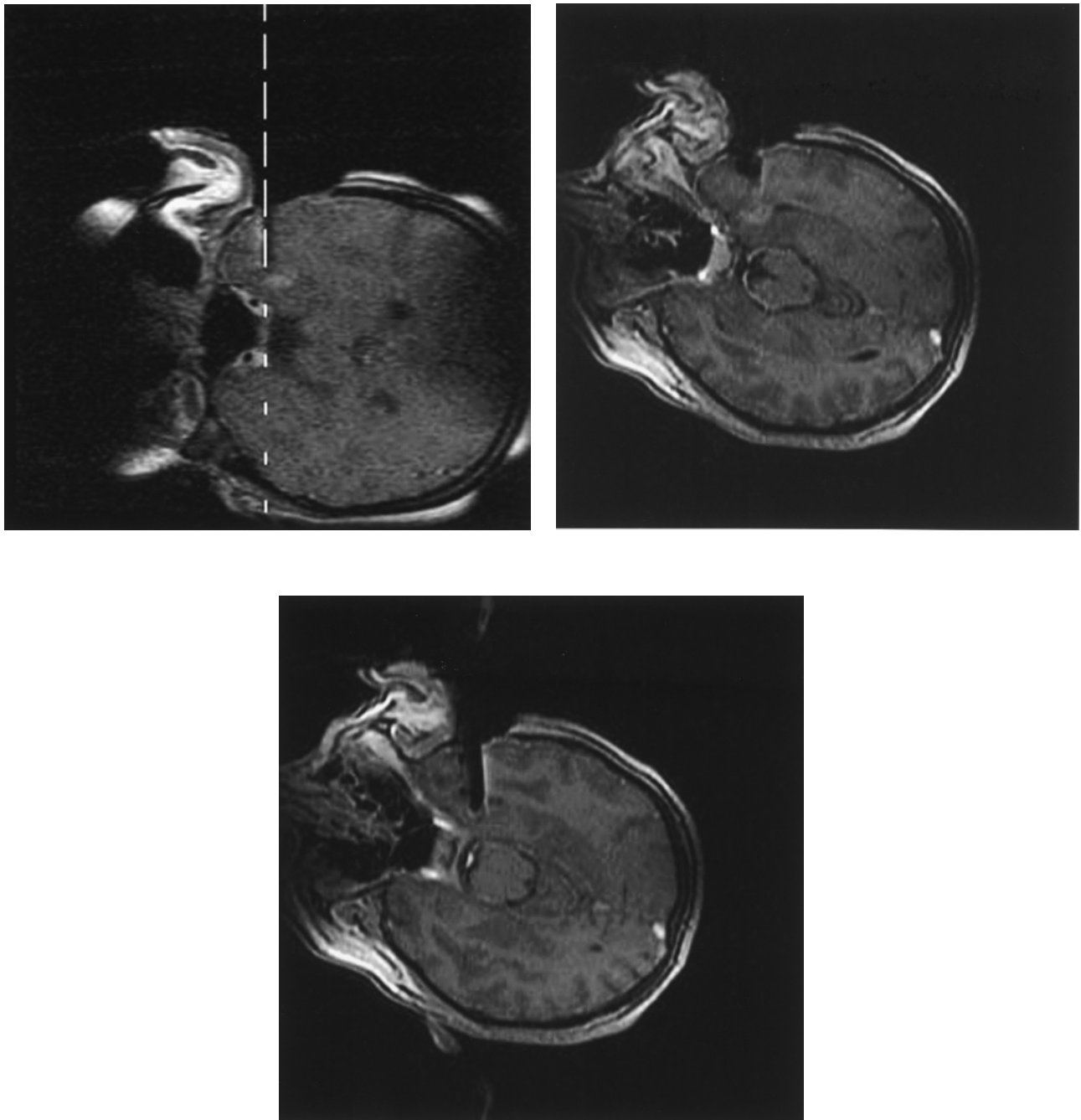


Fig. 2 Patient 8. Topleft. Axial T1 iMRI image after gadolinium, showing an enhancing lesion of the mesial temporal lobe. The dashed line indicates the position of a handheld probe linked to the 3-D optical stereotactic system. The long dashes show the position of the probe itself and the short dashes show its trajectory. The tip of the probe is at the lesion. Top Right. Axial T1 iMRI image shows residual enhancing tissue. Bottom. Axial T1 iMRI image shows complete removal of the lesion.

antiepileptic medications. Examination following left internal carotid injection of sodium amytal confirmed left hemisphere language, and demonstrated adequate support of memory on the contralateral side. EEG prior to injection showed no abnormalities. An MRI scan revealed a mildly enhancing lesion of the medial left temporal lobe. A left temporal craniotomy was performed under general anesthetic with intraoperative MRI (Fig. 2). The lesion was approached via the middle temporal gyrus. After initial resection, which was thought to be complete, further imaging revealed residual pathological tissue which was then removed. Histology was consistent with ganglioglioma.

The patient had an uneventful postoperative course, and at last follow-up, 48 months postoperatively, had only suffered

from a single complex partial seizure 2 months postoperatively. She was not taking any antiepileptic medications.

Case illustration: patient 13

This 27 year-old female had a long history of seizures, of several types, including atonic seizures with drop attacks, and gelastic seizures. Fifteen years before surgery with iMRI, the patient underwent a right frontal craniotomy and subfrontal approach to a hypothalamic lesion. This was only partially resected and the histology showed the lesion to be a hamartoma. Gelastic seizures continued. Five years before surgery with iMRI, the patient underwent a corpus callosotomy. Subsequent to this procedure, disabling drop attacks were

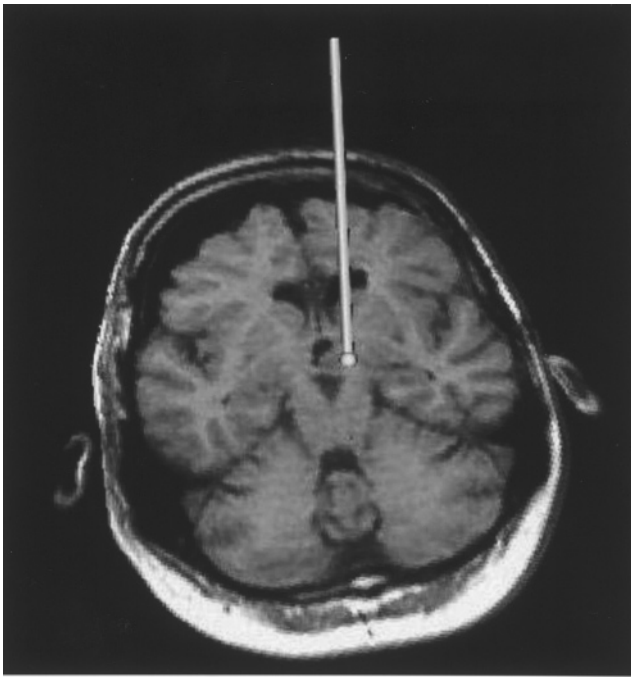
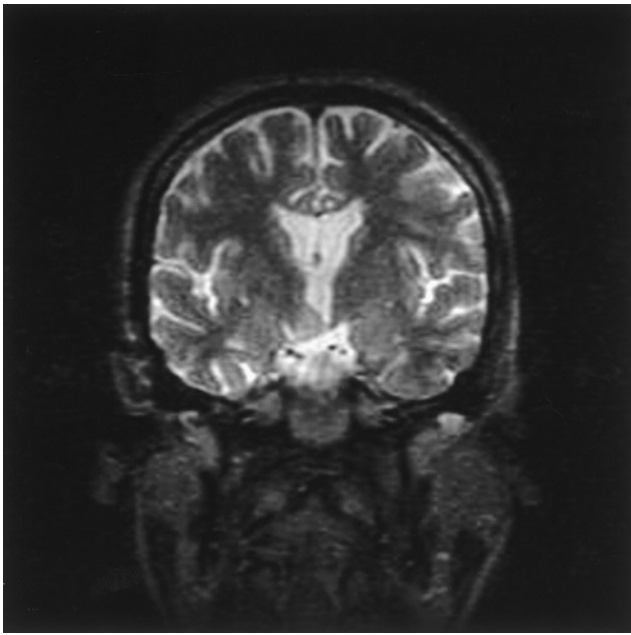


Fig. 3 Patient 13. Top. Coronal T2 iMRI image taken before the commencement of surgery showing a sessile, slightly hyperintense lesion of the right wall of the third ventricle. Bottom. Axial SPGR iMRI image taken during surgery showing the position of the stereotactic probe on the lesion.

significantly improved, however, gelastic seizures continued. Follow-up MRI scans revealed a 2 cm lesion in the right hypothalamus (Fig. 3).

Under general anesthetic, the previous bicoronal incision was reopened and the previous bone plate was removed. Using an operating microscope, an interhemispheric approach was made to the right lateral ventricle. The third ventricle was entered transforaminally and the right hypothalamic lesion was located (Fig. 3) and completely excised. The histology was consistent with hamartoma.

Although the patient was slightly drowsy for several days postoperatively, she made an uneventful recovery. Over 2

months of follow-up, the frequency of gelastic seizures had significantly improved.

DISCUSSION

iMRI has been a major advance for the management of neurosurgical lesions. It provides the surgeon with a navigational tool, as well as real-time confirmation of maximal resection of pathological tissue and exclusion of immediate postoperative complications. Initial reports have concentrated on its application to treatment of neoplastic brain lesions.^{4,6,17} We present here our experience with iMRI for the treatment of lesional epilepsy.

Image-guided surgery has been a major advance in the surgical approach to epilepsy.^{10,13} Image guidance can be used with MRI images merged with CT or functional modalities, as well as preoperative cortical mapping data.¹⁰ Image guided surgery has been found to be particularly effective in defining small areas of cortical dysplasia not evident macroscopically.¹⁰ MRI is essential to modern neurosurgery in general and to image-guided neurosurgery in particular, providing surgeons with excellent anatomical definition and flexibility of multi-planar imaging. Many framed and frameless image-guided technologies have been developed that used preoperatively acquired magnetic resonance images. Yet brain shift is a major drawback of all navigational systems that rely on preoperative imaging data, because during surgery, deformation of the brain tissue occurs resulting in localization errors.¹⁸ This may lead to a loss of reliability of the image-guided tool.

iMRI minimizes these difficulties by using intraoperative acquisition of images. When used in concert with a frameless three-dimensional optical stereotactic system to provide real-time surgical navigation, this can be extremely useful. With iMRI, the imaging data can be updated continually throughout the course of the procedure. The iMRI has been used for a variety of procedures,^{1,3,4,19} this series documents the applicability of iMRI to epilepsy surgery. iMRI provides for intraoperative guidance to the lesion, so that skin incisions, craniotomies and approaches can be optimized, as well as the assurance that lesional tissue is excised minimizing damage to normal brain, and that the resection of such pathology is complete. Theoretically at least it is, therefore, ideal for treatment of benign intraaxial lesions that cause epilepsy. Intraoperative imaging also allows for compensation for brain shift by updating imaging information and neuronavigation systems if used. In our series, iMRI and navigation was successful in all cases in planning of the surgical exposure and approach to the lesion. Given that brain shift can be a significant problem, especially for deep lesions, we feel that iMRI is ideal in approaching deep, benign lesions that present with seizures. We were able to show a complete macroscopic resection in all cases. Clinically there was improvement in all patients, however the period of follow-up is short.

In our series, there were only 1 patient suffered a neurological deficit postoperatively, which resolved over a short period of time. We believe that iMRI with intraoperative guidance allows for accurate planning of exposure and approach and, therefore minimizes the morbidity associated morbidity associated with inaccurately planned exposures and approaches. Total resection of lesions offers the best chance for improvement of epilepsy,¹⁰ and iMRI allows this to occur, as well as providing stereotactic guidance. Whether epilepsy outcome can be further improved by removing additional cortex identified by intracranial extra- or intraoperative recording of ictal and/or interictal EEG is controversial.⁹

Reliable EEG recording in the iMRI poses several technical problems, and our results thus far have been difficult to interpret; further investigation will demonstrate whether the additional data provided by this technique provides measurable benefit.

CONCLUSIONS

iMRI and craniotomy is an effective strategy for intraaxial lesions that cause seizures. It allows for accurate planning and approach as well as confirmation of complete resection. We believe it minimizes adverse effects of surgery and may improve long-term results, particularly seizure outcome.

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