Utility of neuronavigation and neuromonitoring in epilepsy surgery

A review

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The management of medically refractory epilepsy poses both a valuable therapeutic opportunity and a formidable technical challenge to epilepsy surgeons. Recent decades have produced significant advancements in the capabilities and availability of adjunctive tools in epilepsy surgery. In particular, image-based neuronavigation and electrophysiological neuromonitoring represent versatile and informative modalities that can assist a surgeon in performing safe and effective resections. In the present article the authors discuss these 2 subjects with reference to how they can be applied and what evidence supports their use. As technologies evolve with demonstrated and potential utility, it is important for all clinicians who deal with epilepsy to understand where neuronavigation and neuromonitoring stand in the present and what avenues for improvement exist for the future. (DOI: 10.3171/FOC/2008/25/9/E17)

KEY WORDS • electrocorticography • epilepsy surgery • frameless stereotaxy • image guidance • neuromonitoring • neuronavigation

Epilepsy claims 4–10 individuals per 1000 population—translating to roughly 40 million people worldwide and affects 50-100 new cases per 100,000 persons each year.17,83,104 In addition to the enormous social impact and increased mortality associated with this condition, the annual economic burden to Europe approached 16 billion Euro in 2004 alone.19,75

Antiepileptic drug therapy, the mainstay of epilepsy treatment, successfully leads to long-term remission in ~70% of patients.45 In the remaining ~30%, pharmacotherapy is intolerable, ineffective, or inadequate. A recent meta-analysis of studies evaluating patients with medically uncontrolled epilepsy undergoing temporal or extratemporal resections found that >80% achieved improved seizure control, with a median of 67% rendered seizure free.98 These aggregate results mask considerable variability in outcomes for different underlying pathological entities; however, surgery generally represents a viable and efficacious option for many patients in whom medical therapy falls short.

Despite its success, the neurosurgical treatment of epilepsy remains a clinical decision-making and technical challenge for which there is still room for improvement. Recent advances in the capabilities and dispersion of intraoperative neuronavigation and neuromonitoring underscore how the modern epilepsy surgeon is becoming increasingly armed with adjunctive technologies that hold the promise to improve surgical outcomes. In the present article we will discuss how these 2 modalities can be applied in the treatment setting and we detail the existing evidence for their impact on treatment success.

Neuronavigation

Image-guided neuronavigation uses preoperative, intraoperative, or real-time imaging to allow the surgeon to understand spatial relationships within the brain that are not visible by line-of-sight. Preoperative imaging-based neuronavigation utilizes the principle of stereotaxy to reference Cartesian coordinate system–derived 3D spatial information, obtained in real time from the patient, to that of previously acquired and 3D reconstructed patient-based imaging. Similarly, intraoperative CT or MR imaging can be

Abbreviations used in this paper: DCS = direct cortical stimulation; DT = diffusion tensor; ECoG = electrocorticography; EEG = electroencephalography; FDG = fluorodeoxyglucose; fMR = functional MR; MEG = magnetoencephalography; SSEP = somatosensory evoked potential; TLE = temporal lobe epilepsy.
Anatomical Guidance

Defining one’s location relative to surrounding neurovascular structures is imperative to performing safe and effective epilepsy surgery. The utility of preoperative neuronavigation in providing anatomical guidance can take many forms. For example, neuronavigation used preoperatively can assist with planning of the bone-flap position to maximize safe access during interhemispheric approaches to corpus callosotomies (Fig. 1), intraoperatively to select the optimal approach angle during transtemporal approaches to temporal lobectomies, and diagnostically when placing recording depth electrodes in precise anatomical locations such as the amygdalae.\textsuperscript{27,56,105} Neuronavigation can also reduce the invasiveness of procedures by eliminating the requirement to expose visible landmarks. For instance, the placement of subdural strip electrodes through a single enlarged temporooccipital bur hole using fluoroscopic guidance can be employed to localize the seizure focus in patients with TLE without the need for a conventional craniotomy.\textsuperscript{49} Ng et al.\textsuperscript{57} have described how frameless stereotaxy helps achieve a transcortical transventricular endoscopic approach by which to resect hypothalamic hamartomas associated with refractory epilepsy. In their hands, this approach resulted in a shorter recovery time than a more traditional transcallosal approach. When a high degree of targeting certainty is required, neuronavigation can usually provide sufficient precision and accuracy and thus eliminate the requirement to use conventional frame-based stereotaxy (Fig. 2). Depth electrode placement into specified parenchymal targets can also be achieved via small cranial exposures using CT and/or MR imaging-guided neuronavigation systems, with a reported accuracy of 2–3 mm.\textsuperscript{47,49} In a large retrospective series of 217 patients who underwent neuronavigation-guided placement of over 3000 depth electrodes at the Montreal Neurological Institute, De Almeida and colleagues\textsuperscript{12} collected data that permitted a conclusive decision regarding whether to proceed with surgery in 96% of cases.

Intraoperative image-based neuronavigation has the distinct advantage that acquired images more closely reflect the actual spatial relationships present at the time of surgery. Intraoperative brain deformations, resulting from such influences as patient positioning and violation of the cranial vault, pose a significant threat to the accuracy of neuronavigation systems that rely on rigid registration algorithms to preoperative imaging. In one series using 3D ultrasonography to examine the degree of discrepancy between preoperative imaging and actual intraoperative brain geometry upon dural opening, vertical and horizontal shifts

<table>
<thead>
<tr>
<th>Category of Neurosurgery</th>
<th>Technique</th>
<th>Temporal Lesion</th>
<th>Temporal Nonlesion</th>
<th>Extratemporal Lesion</th>
<th>Extratemporal Nonlesion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neuronavigation</td>
<td>preop conventional MRI</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>DTI</td>
<td>yes</td>
<td>yes</td>
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<td></td>
<td>intraop US</td>
<td>yes</td>
<td>no</td>
<td>no</td>
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</tr>
<tr>
<td></td>
<td>preop MEG</td>
<td>not essential</td>
<td>not essential</td>
<td>yes, for functional mapping of motor, sensory, &amp; visual cortex as needed</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>fMRI</td>
<td>yes, if dominant</td>
<td>yes, if dominant</td>
<td>occasionally required</td>
<td>often required to identify the ictal onset zone</td>
</tr>
<tr>
<td></td>
<td>FDG-PET</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
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<td>invasive monitoring (grid/strip/depth electrodes)</td>
<td>yes, if dominant, close to language</td>
<td>yes, if dominant, close to language</td>
<td>occasionally required</td>
<td>often required to identify the ictal onset zone</td>
</tr>
<tr>
<td></td>
<td>ECoG</td>
<td>rarely used</td>
<td>occasionally used</td>
<td>occasionally used</td>
<td>often used postresection to assess for spike waves</td>
</tr>
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<td></td>
<td>DCS</td>
<td>can be used to map language in awake craniotomies</td>
<td>can be used to map language in awake craniotomies</td>
<td>in awake craniotomies to localize language/sensorimotor cortex; in anesthetized craniotomies to localize motor cortex</td>
<td>in awake craniotomies to localize language/sensorimotor cortex; in anesthetized craniotomies to localize motor cortex</td>
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<tr>
<td></td>
<td>continuous train of 5 CST monitoring</td>
<td>no</td>
<td>no</td>
<td>yes, if periradical</td>
<td>yes, if periradical</td>
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*CST = corticospinal tract; US = ultrasonography.
of up to 8 and 10 mm were observed, respectively. Intraoperative CT or MR imaging can provide updated data at 1 time or more points during the procedure and deliver excellent image quality. Intraoperative MR imaging may provide enhanced anatomical guidance during epilepsy surgery by permitting a more precise resection of desired structures and thus limiting damage to uninvolved brain tissue; however, no proof of improved complication rates has been published. Schwartz et al. have proposed that intraoperative MR imaging can better standardize the resection of tissue during radical amygdalohippocampectomies, having demonstrated comparable extents of resection on postoperative images in 5 patients who underwent intraoperative MR imaging-guided surgery. This approach may reduce the variability in surgical outcomes, although it also remains to be demonstrated. Larger controlled studies are needed to better establish the potential benefits of improved anatomical guidance with intraoperative MR imaging in epilepsy surgery, especially in light of its considerable cost.

Another method to compensate for brain shift is the use of one of a growing number of sophisticated compensation algorithms involving expensive computational software programs and intraoperative registration updates; however, outside of biomechanical brain models, sufficient validation and testing data are lacking. A simpler means to verify navigational information obtained from preoperative imaging-based neuronavigation is to regularly confirm the location of anatomical landmarks using real-time imaging techniques. Intraoperative ultrasonography is a useful and typically readily available confirmatory navigation tool, even reported to be capable of visualizing certain cortical dysplastic lesions with greater resolution than that of preoperative MR imaging. Despite its utility, user-dependent interpretation and often relatively poor image quality render ultrasonography an imperfect real-time navigation modality.

Lesion Localization and Resection Assessment

Lesions that are visible on preoperative images are easily amenable to the benefits of neuronavigation. Precise localization of lesions assists with planning a safe and efficient approach and can also permit an assessment of the extent of resection. Some evidence suggests that neuronavigation-assisted TLE surgery may reduce the rates of postoperative complications by narrowing the approach while maintaining the rate of successful seizure control. In a single-surgeon comparison of 39 cases using navigation compared with 22 without, both of which included a combination of cryptogenic and symptomatic causes, the overall

Fig. 1. Neuronavigation and surgical images obtained in an 8-year-old boy who had previously undergone anterior corpus callosotomy and experienced recurrent atonic seizures. It was proposed that he undergo resection of the posterior corpus callosum for seizure control. In this intraoperative screen-save image, the upper images depict axial, coronal, and sagittal views that reveal the interhemispheric approach to the splenium of the corpus callosum. The blue line represents the image guidance probe that was positioned through the field such that its tip was resting adjacent to the deep and posterior extent of the exposure. These 3 upper images were saved on the screen, and the lower intraoperative image with the microscope shows the approach to the vein of Galen (labeled V), which demarcates the posterior extent of resection (anterior is to the left). Image guidance is useful in these cases, especially when the splenium is curved downward and steep.

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complication rates were 8 and 22%, respectively, after a minimum follow-up of 2-years. Interestingly, this same study found no differences in mean surgical time, duration of hospital stay, and postoperative seizure reduction. Indeed, direct evidence for improved outcomes following neuronavigation-assisted TLE surgery is lacking, but it is possible given the ability to verify the extent of resection afforded by intraoperative neuronavigation and evidence suggesting that the extent of resection is directly correlated with the success of seizure control.

A number of authors have described the use of intraoperative neuronavigation as a method of ensuring a complete resection of desired tissue. Buchfelder et al. extended the resection in 3 of 58 tailored temporal resections for epilepsy following 0.2-T intraoperative MR imaging verification of the extent of surgery. The limited number of articles available in the literature suggests that the rate of further resection appears to rise as the field strength and, thus resolution, of the MR imaging device increases. For example, 5 of 13 benign lesional epilepsy cases performed using intraoperative 0.5-T MR imaging had further resections performed as a result of the intraoperative images. Kaibara et al. reported a series of 14 patients undergoing anterior temporal lobectomy or selective amygdalohippocampectomy for TLE. The authors used intraoperative 1.5-T MR imaging to identify 7 patients with residual unresected tissue and 1 with an occult hematoma, in all of whom the lesions were then successfully dealt with during the same operation. Whether performing these confirmatory steps results in demonstrable differences in surgical outcomes remains undetermined.

**Functional Localization of Eloquent Brain Linked to Neuronavigation Platforms**

Accurate localization of eloquent brain regions is of critical importance during resections of nearby epileptogenic foci or lesions. Integrating preoperative image-based neuronavigation with functional imaging modalities, such as FDG-PET, fMR imaging, and MEG, can provide a wealth of information allowing preservation of eloquent brain areas and more aggressive resections without increased morbidity.

**Fluorodeoxyglucose-PET.** Fluorodeoxyglucose-PET imaging is acquired with the patient performing a desired task while FDG uptake, a marker for cerebral metabolism that indirectly correlates with neuronal activity, is measured and compared with reference conditions. Although notably providing the flexibility to test any task-related brain function, PET-based neuronavigation is not common due in part to its relatively poor temporal and spatial resolution. For example, Sobottka et al. matched preoperative MR imaging data with FDG-PET–acquired language mapping and used the fused image for frameless navigation in 7...
patients with left-sided gliomas. Using intraoperative electrocortical stimulation to confirm speech localization, the authors found discordant targeting in 3 of the 7 cases. Other challenges relating to FDG-PET–based neuronavigation include its requirement for the invasive use of a radioactive tracer (which also requires access to a cyclotron), generally high cost, and low availability. Indeed, the sensitivity and specificity of FDG-PET functional imaging does not currently appear adequate to safely perform epilepsy surgery in the vicinity of eloquent cortex.

Functional MR Imaging. Similar to FDG-PET, fMR imaging measures neuronal activity indirectly by detecting blood oxygen level-dependent changes in the MR signal associated with neuronal activity-related alterations in local perfusion. Advantages of fMR imaging over FDG-PET include its higher spatial resolution (typically 2–5 mm) and its noninvasiveness. Despite these positive attributes, the latency of observed fMR imaging signal changes is several seconds, making its temporal resolution relatively poor. For neuronavigation purposes, fMR imaging is typically used to localize primary motor and sensory cortices along with language areas. While motor and sensory areas can be relatively reliably localized, the precision for language localization is relatively weak and variable in the literature. For instance, Roux et al. compared language areas activated by naming and verbal generation tasks with intraoperative speech mapping using electrocortical stimulation in 14 patients with left hemisphere tumors. Of the 22 language sites identified using DCS, only 5 were concordant with sites identified by fMR imaging. In contrast, Carpentier et al. reported concordance in intrahemispheric language maps generated by fMR imaging and electrocortical stimulation in patients with mesial TLE. Such inconsistencies suggest that current fMR imaging–based localization of language may be too unreliable to permit safe surgical planning of nearby resections, and other localization techniques such as invasive electrocortical stimulation are still required in these cases.

A more recent development in the use of fMR imaging for neuronavigation has been its integration with DT imaging data. Diffusion tensor imaging is an MR imaging–based sequence that can demonstrate white matter tracts by measuring the diffusion of water molecules, whose movement is relatively restricted to remain parallel to tracts. This integrated neuronavigation has been employed for visualizing the pyramidal tracts and optic radiations during surgery for nearby lesions. For neuronavigation purposes, fMR imaging is typically used to localize primary motor and sensory cortices along with language areas. While motor and sensory areas can be relatively reliably localized, the precision for language localization is relatively weak and variable in the literature. For instance, Roux et al. compared language areas activated by naming and verbal generation tasks with intraoperative speech mapping using electrocortical stimulation in 14 patients with left hemisphere tumors. Of the 22 language sites identified using DCS, only 5 were concordant with sites identified by fMR imaging. In contrast, Carpentier et al. reported concordance in intrahemispheric language maps generated by fMR imaging and electrocortical stimulation in patients with mesial TLE. Such inconsistencies suggest that current fMR imaging–based localization of language may be too unreliable to permit safe surgical planning of nearby resections, and other localization techniques such as invasive electrocortical stimulation are still required in these cases.

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Magnetoencephalography. Magnetoencephalography is a combined functional and anatomical imaging modality that lends itself well to neuronavigation. An arrangement of superconducting quantum interference devices detects the magnetic fields induced by neuronal currents, allowing the localization of the field sources within 3D space. Unlike EEG-detected electrical currents that become distorted due to the heterogeneous conductivity of tissues, magnetic fields suffer minimal distortion and permit more accurate source localization. The spatial resolution of MEG is fairly high, reported to be ~ 2 mm. Coregistration of these data with conventional anatomical MR imaging results in a composite image sequence that can be used in neuronavigation systems. Perhaps the greatest strength of this noninvasive technique is its unmatched combination of temporal and spatial resolution; concurrently, its greatest weaknesses are arguably its considerable requirement for specialized personnel and high cost. Magnetoencephalography is increasingly being employed for neuronavigation to safely resect lesions adjacent to eloquent cortex (Fig. 4). Several studies report good

**Fig. 3.** Oblique (A) and axial (B) DT images obtained in a 10-year-old girl with complex partial seizures and a right premotor dysembryoplastic neuroepithelial tumor (DNET). The proximity of the deep side of the lesion to ipsilateral corticospinal tracts, indicated in yellow, and corticospinal/corticopontine fibers, indicated in purple, can be readily appreciated. The lesion was removed via an anterior approach using neuronavigation, intraoperative ultrasonography, and continuous train of 5 motor mapping. The patient underwent a gross-total resection, and awoke postoperatively without a deficit.
correlation between preoperative MEG functional data, intraoperative maps of sensory and motor evoked potentials, and electrocortical stimulation. For instance, in a study of 11 patients undergoing epilepsy surgery the authors found a perfect correlation between the somatosensory hand area determined by MEG-based neuronavigation with that of EEG recordings using subdural electrode arrays in all cases. Furthermore, Korvenoja et al. found concordance between MEG and intraoperative cortical mapping of the central sulcus in all 15 patients examined, whereas a similar agreement between fMR imaging and cortical mapping occurred in only 11 of those 15. With relatively accurate and precise functional localization along with inherently high-quality anatomical imaging, MEG-guided neuronavigation may allow the surgeon to confidently resect more aggressively without violating functional cortical areas.

Fig. 4. Utility of MEG linked to image guidance in directing the safety of craniotomy, brain mapping, and lesion excision in a 14-year-old girl with focal motor seizures caused by a DNET in the premotor gyrus. A: Intraoperative screen-save image with 3D reconstruction and color-coding of the motor cortex (dark green), somatosensory cortex (light green), and superior sagittal sinus with associated bridging veins (red). The navigation pointer (represented by blue line) is placed on the motor strip. B: Intraoperative photograph of the right-sided exposure with the dura reflected medially (left) toward the sagittal sinus. The navigation pointer (B) is placed on the motor strip, also marked with the letter A. This location of the motor strip was confirmed by direct motor cortical stimulation. C: Postoperative photograph showing removal of the lesion, preservation of the draining veins toward the sagittal sinus, and maintained integrity of the motor cortex. The patient awakened without deficit and has been seizure free without the use of medication for over 3 years.
bining fMR imaging, anatomical MR imaging, DT imaging, and 3D ultrasonography to automatically update navigation imaging and correct for brain shift. As further evidence accumulates and the technologies become more widespread, neurosurgeons will be able to choose which systems provide the most reliable information to assist with cortical resections at the time of epilepsy surgery.

Epileptogenic Spike Source Localization and Resection

Nonlesional medically refractory epilepsy represents a surgical challenge requiring accurate and precise localization of the epileptogenic zone. Multiple imaging modalities can localize epileptiform activity with varying degrees of spatial and temporal resolution, and can be merged with anatomical imaging to function as a neuronavigation tool. Interictal spike–triggered fMR imaging, interictal FDG-PET, and ictal SPECT may be used to localize neocortical seizure foci. However, these aforementioned modalities are rarely used because of their relatively poor resolution or many logistical difficulties in acquiring images. Magnetoencephalography has emerged as the leading neuronavigation modality for the localization of epileptogenic foci, predominantly due to its aforementioned superior combination of spatial and temporal resolution.

Magnetoencephalography in conjunction with anatomical imaging is a powerful technique that permits the visualization of epileptic spikes within the brain. In epilepsy cases in which no offending anatomically identifiable lesion can be visualized and in which the ictal onset or irritative zone cannot be localized using conventional means, MEG can identify the anatomical location of epileptogenic spike clusters and permit an image-guided focal resection of this region. Minassian et al. have found a perfect correlation between the location of interictal MEG spike foci mapped using neuronavigation and that of EEG epileptiform discharges identified using subdural electrodes in 10 of 11 patients studied. Other studies have demonstrated similarly high correlation rates both for TLE and non-TLE. Magnetoencephalography can also be used to guide subdural grid placement over regions rich in spike sources when ultraprecise cortical localization of the seizure onset zone is required. This technique can even be employed in refractory status epilepticus cases to target and resect the offending region of spike clusters. A major strength of MEG-based neuronavigation is the ability to simultaneously visualize seizure onset zones, eloquent regions derived from functional mapping, and brain lesions visible on MR imaging when present.

Good success rates have been reported following neuronavigation-guided resection of MEG spike source clusters (Fig. 5). This is particularly true for cases of extrahippocampal lesional epilepsy with irritative foci extending beyond the lesion. For example, 11 of 12 pediatric patients suffering from lesional extrahippocampal epilepsy became seizure free with multimodal neuronavigation-guided surgery. A similar rate of success has been observed in adult patients.
seizure free following MEG-guided cortical excision in addition to lesionectomy.\textsuperscript{68} Slightly lower but substantial success is reported for normal or subtle nonfocal MR imaging findings, where MEG-guided resection for intractable epilepsy provided good seizure control in 17 of 22 children.\textsuperscript{76} Indeed, in all 17 successfully treated patients there was an MEG cluster in the final resection area. In cases of recurrent seizures following surgery, patients may exhibit residual MEG spike source clusters in the epileptogenic zone.\textsuperscript{32,54} Eleven of 17 children with recurrent seizures had good surgical outcomes after further MEG-guided resection, suggesting that MEG can still function as a relatively reliable tool even for recurrent focal resections.\textsuperscript{54} The authors of a recent report described a small series of patients with refractory status epilepticus in whom MEG-based neuronavigation guided the focal resection of spike clusters.\textsuperscript{53} In 5 patients with no response to all other treatment measures, 2 were rendered seizure free. In summary, a rapidly growing body of literature attests to the ability of MEG to guide clinically successful nonlesional epilepsy surgery and arguably establishes MEG as the most powerful imaging modality currently available to guide epilepsy surgery.

Neuromonitoring

Neuromonitoring is classically used as a surgical tool to help reduce the risk of iatrogenic injury and identify the function of structures or regions of interest.\textsuperscript{14} Examples used for a variety of neurosurgical procedures include SSEPs and electromyography. Epilepsy surgery employs its own set of relatively unique neuromonitoring practices that assist the surgeon in identifying eloquent regions and represent the gold-standard method for defining epileptogenic zones (Table 1). While standard neuromonitoring is often used in epilepsy surgery, the following sections will describe the particular techniques utilized by surgeons to help deal with epilepsy-related disease.

Electrocorticography, Depth Electrode Recordings, and DCS

Electrocorticography involves the invasive placement of recording electrodes directly onto the surface of the brain. Penfield and Jasper\textsuperscript{3} are generally credited with pioneering the use of ECoG for the delineation and subsequent resection of epileptogenic regions identified by recording interictal spikes intraoperatively. Since that time, ECoG has become a common intraoperative tool to measure interictal discharges and define functional areas during epilepsy surgery, and a perioperative modality between staged procedures to record and localize ictal activity.\textsuperscript{5,87} Depth electrodes can be inserted into subcortical areas to listen for ictal or interictal epileptic events and are commonly combined with subdural cortical electrode grids to provide additional localizing information during perioperative neuromonitoring.\textsuperscript{45} Recordings obtained perioperatively can complement those obtained intraoperatively by allowing one to capture a greater amount of ictal and interictal re-
have reviewed similar surgeries and potentially minimize the unnecessary resection of mining the extent of resection to maximize seizure control. Evidence suggests that ECoG may provide a means of determining the extent of resection to maximize seizure control and potentially minimize the unnecessary resection of uninvolved tissue. In a prospective series of 140 consecutive mesial temporal resections, 67% of the patients were rendered seizure free at a minimum of 18 months postoperatively. Although the overall size of the hippocampal resection did not correlate with seizure control, the presence of postresection residual hippocampal interictal epileptiform activity predicted worse seizure outcomes and suggested that hippocampal ECoG may be a useful indicator of the need for further resection. Other reports do not support a predictive value for seizure outcome based on the presence of preresection ECoG-identified interictal discharges outside the area of planned resection. Clearly, further prospective studies are required to define the potential role for ECoG in improving the efficacy and safety of mesial temporal sclerosis or gliosis surgery.

Extratemporal lesional epilepsy represents another category of epilepsy surgery in which ECoG has provided a measurable benefit in ensuring optimal seizure control. For instance, in a series of 25 patients with lesion-related frontal lobe epilepsy, the most significant correlation with postoperative Engel Class I outcome was observed in patients who underwent complete lesionectomy and removal of perilesional epileptogenic tissue and in whom postexcision ECoG-recorded epileptiform activity was absent distant to the resection border. These findings agree with those for lesional TLE surgery and underscore the utility of identifying and excising extratemporal epileptogenic foci.

Epilepsy stemming from nonlesional sources or poorly defined lesions can be successfully treated with ECoG-guided surgery. For example, Iida and colleagues have demonstrated the successful use of ECoG to direct the focal cortical resection of epileptogenic tissue associated with intractable porencephaly-related epilepsy. In 7 of 8 cases, intraoperative ECoG revealed interictal epileptiform areas extending beyond the margins of the cyst. After a minimum of 1 year of follow-up, 6 patients had excellent seizure outcome (Engel Class I) with 2 having >90% seizure reduction without complications. Another good example is surgery for malignant rolandic-sylvian epilepsy, a therapeutically challenging form of epilepsy with medically refractory sensorimotor seizures, normal brain imaging findings, frontocentrotetemporal EEG spikes, rolandic-sylvian spike sources on MEG, and cognitive problems. Ōsubo et al. have retrospectively reported on 7 children with malignant rolandic-sylvian epilepsy who ultimately underwent ECoG-guided focal cortical resections and multiple subpial transections. At a mean follow-up duration of 30 months, 3 patients were seizure free and 4 had seizures rarely. Importantly, no patients suffered new permanent deficits in sensorimotor or cognitive functions. Pondal-Sordo and colleagues have reviewed similar surgeries performed in 52 patients and determined that interictal ECoG was the most useful form of surgical guidance to predict a good seizure outcome. Changes in ECoG activity have also been used during corpus callosotomies as a means of determining the extent of surgery required and of predicting the postoperative seizure outcome; however, conflicting reports cast doubt upon its ability to influence these factors, and thus its use is not uniformly accepted. In summary, the unparalleled precision afforded by ECoG can in many cases permit effective and relatively safe surgical management of nonlesional epilepsy that is intimately related to eloquent brain regions.

Both lesional and nonlesional procedures for treating extratemporal epilepsy in the vicinity of sensorimotor and...
or language cortices are often amenable to brain mapping using DCS. Direct cortical stimulation is performed by applying focal cortical stimulation with a hand-held bipolar electrode and delivering brief low-current stimulation either of constant 60 Hz or with a train of 5 high-frequency pulses. The latter train of 5 technique may have a lower risk of inducing intraoperative seizures, in the range of 1%. Language functions, such as repetition and comprehension, necessitate the testing of patients while awake. Stimulation over language areas generally results in a disturbance of function, which is manifested by an impaired ability to complete the task. Sensomotor functions can be measured in awake patients by obtaining feedback regarding their physical sensations during stimulation. In anesthetized patients, peripheral nerve stimulation, such as that of the median nerve, can be recorded across the rolandic region using electrode arrays. The recorded SSEPs demonstrate a reliable phase reversal across the central sulcus, permitting accurate localization of the adjacent primary motor and sensory cortices. Direct cortical stimulation of the presumed motor cortex can then be performed with confirmatory motor evoked potentials subsequently recorded peripherally. In the absence of paralytic agents, muscle contractions may also be observed at sufficient stimulation intensities, such as tongue and face movements evoked by stimulating the base of the rolandic cortex. Generally considered the gold standard method for precisely localizing these functions, DCS is frequently invaluable in preserving function during epilepsy surgery.

Multimodal Neuromonitoring Strategies for Surgery

While the preceding discussions have dealt with neuromonitoring techniques as relatively independent topics, the real-world application of these modalities is increasingly multimodal (Table 1). For example, multiple methods of intraoperative neuromonitoring play important roles in extratemporal epilepsy to identify functional cortical landmarks that aid the neurosurgeon and epileptologist in creating the necessary map for subsequent cortical resection. Typically, the central sulcus is identified by identifying phase reversals from an electrode array placed across adjacent gyri (Fig. 6). This is then followed by DCS of the presumed motor cortex and registering of a distal motor response by contralateral electromyographic recordings. Then, a subdural grid is implanted, and perioperative recordings from the grid are made to corroborate what was found at the time of surgery. A comprehensive surgical map is then created using software programs to draw the planned resection area onto a digital image taken at the time of surgery (Fig. 7). This image is then used by the neurosurgeon to resect the primary epileptogenic zone.

Recently, our center has also been employing the technique of “trains of 5” continuous corticospinal tract stimulation and monitoring to safely resect lesions adjacent to the rolandic region (Fig. 8). This has enabled an aggressive approach to lesions in this area and can be very useful to predict functional outcome of the patient after surgery.

Conclusions

Modern intraoperative neuronavigation and neuromonitoring function as a highly accurate and versatile set of additional eyes that guide the modern epilepsy surgeon in performing safe and effective epilepsy surgery. As these technologies have continued to improve and become broadly adopted, a growing body of literature speaks to their utility and efficacy. Despite their positive impact, no epilepsy surgery therapy has a 100% success and safety rate, and future generations of neuronavigation and neuromonitoring devices have room to improve the way neurosurgeons can meet the needs of individuals suffering from epilepsy.

Disclaimer

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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