**Epilepsy Surgery**

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**NOTE FROM THE PUBLISHER:**
This publication has been developed without involvement of or review by the American Board of Psychiatry and Neurology.
Epilepsy Surgery

Paramita Das, MD, Thomas R. Henry, MD, and Aviva Abosch, MD, PhD

INTRODUCTION

Clinicians who are managing patients with drug-resistant epilepsy must consider whether epilepsy surgery is a reasonable alternative for these individuals. Practitioners therefore should understand the indications, risks, and benefits of surgery, as well as the durability of the surgical outcomes. In this article, we review the most common and efficacious surgical interventions for epilepsy, including temporal lobectomy, amygdalohippocampectomy, cerebral lesionectomy with or without additional cortical resection, nonlesional corticectomy, corpus callosotomy, and multiple subpial transections.

REFRACTORY EPILEPSY: DEFINITION, EPIDEMIOLOGY, AND CONSEQUENCES

Epilepsy affects nearly 1% of the U.S. population. Treatment with an antiepileptic medication results in seizure remission in only 60% to 70% of patients.1 Seizure control is crucial for clinical as well as psychosocial reasons. Patients with epilepsy are at greater risk of death than are age-matched controls without epilepsy.2 This increased risk is mostly seen in young people with treatment-refractory epilepsy. Trauma, suicide, pneumonia, and status epilepticus have all been identified as causes of death in people with epilepsy, and are seen more frequently in these individuals than in the general population.3,4 Sudden unexpected death in epilepsy (SUDEP) is also increasingly recognized as a cause of death in this patient population, especially in those who experience more than 3 generalized tonic-clonic seizures per month.5 The fear of personal injury or injury to others results in restrictive lifestyle changes, such as limitations on driving.6 There is also a societal stigma associated with epilepsy, and patients may at times feel as if they are a burden to others.7 Women trying to conceive have to be concerned with the teratogenic nature of all antiepileptic medications. Epilepsy, even when well controlled, is not a benign condition and has clinical and psychosocial consequences. For all of these reasons, surgical approaches should be considered for patients with medically refractory epilepsy.
**PRINCIPLES OF SELECTION FOR EPILEPSY SURGERY**

Although antiepileptic drugs (AEDs) should be considered the first line of therapy for the treatment of epilepsy, there are specific epileptic syndromes that respond poorly to medications and yet are associated with excellent outcomes in response to surgery. Early intervention in these patients provides the best opportunity for seizure freedom and complete psychosocial rehabilitation. It is estimated that only 1500 of the nearly 100,000 eligible patients in the United States undergo such surgical procedures annually. There are many potential explanations for the small number of epilepsy surgeries, including patient concerns about complications as well as misconceptions about epilepsy surgery candidacy among referring physicians, but the root cause(s) remains an area of active inquiry.

Ideally, the goals of resective surgery for the treatment of epilepsy are freedom from seizures, elimination of the need for anticonvulsant medications, and absence of injury to eloquent cortex (with potentially permanent new deficits in motor, sensory, or language functions) and other complications of the surgery. With improvements in preoperative evaluations and surgical technique, children under the age of 3 years, as well as patients older than 50, are now considered for epilepsy surgery. The American Academy of Neurology (AAN) has published clinical practice guidelines recommending that patients with disabling complex partial seizures who have failed first-line AEDs should be considered for epilepsy surgery. The definition of “failure of first-line AEDs” is not delineated in this recommendation, and no definitive guidelines are provided about when to refer children for surgical evaluation. In practice, however, clinicians often wait longer because there can be regression of seizures in children with epilepsy. The International League Against Epilepsy (ILAE) recommends consideration of surgery for children with uncontrolled seizures—defined as failure of 2 or more appropriate drugs—or disabling seizures, or with disabling side effects from AEDs. The ILAE also recommends surgical referral for children without an electroclinical syndrome when there is a lesion amenable to removal, and for any infant or toddler with seizures. Patients with drug-resistant epilepsy should be reconsidered for epilepsy surgery at least every 3 years, as new technologies are developed on a regular basis. Finally, although not addressed in either the AAN or ILAE guidelines, women interested in becoming pregnant should be considered for epilepsy surgery because of the teratogenic nature of many antiseizure medications.

**SURGICAL PROCEDURES AND OUTCOMES**

The following sections describe the most common epilepsy conditions for which surgery might be appropriate, as well as the preoperative evaluation, surgical indications, risks, and potential benefits for each; a brief description of the surgical procedures is also provided. Outcomes of surgery are most commonly classified using Engel’s system (Table).

**TEMPORAL LOBECTOMY AND AMYGDALOHIPPOCAMPECTOMY FOR TEMPORAL LOBE EPILEPSY**

**Evaluation**

Patients with unilateral mesial temporal lobe epilepsy (MTLE) are in general among the most favorable of candidates for epilepsy surgery, although patients with the less common syndromes of neocortical temporal lobe epilepsy (TLE) also can benefit considerably from resective therapy.
Patients with MTLE typically display a characteristic symptom complex (see Epilepsy Board Review Manual [EBRM], Volume 1, Part 113). MTLE often begins in the latter part of the first decade of life and initially responds to medication, but disabling complex partial seizures return in adolescence and become refractory to antiepileptic medication. A rather different natural history of seizure progression attends severe limbic system insults of early or later adulthood, such as herpes encephalitis, in which some patients move rapidly from acute seizures during the acute injury through an abbreviated latent phase into highly refractory complex partial seizures of MTLE. Various other temporal patterns of seizure progression and refractoriness are common. The auras may be viscerosensory or experiential in nature, with a rising epigastric sensation typical of the former and a déjà-vu sensation typical of the latter. Interestingly, febrile seizures are observed in 3% of all children, but 40% of all patients with MTLE have a history of febrile seizures in childhood. A history of febrile seizures has also been shown to be a strong predictor of a good surgical outcome.14

Mesial temporal sclerosis represents a specific pattern of pyramidal cell loss and gliosis, with sector CA1 of Lorente de Nó most severely affected, followed by the hilus of the dentate gyrus and adjacent sector CA3. Relative preservation of neurons in CA2 and subiculum of the granule cell layer

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**Table.** Engel’s Classification of Postoperative Outcome

**Class I: Free of disabling seizures***
- A: Completely seizure free since surgery
- B: Nondisabling simple partial seizures only since surgery
- C: Some disabling seizures after surgery, but free of disabling seizures for at least 2 years
- D: Generalized convulsions with antiepileptic drug discontinuation only

**Class II: Rare disabling seizures (“almost seizure free”)**
- A: Initially free of disabling seizures but has rare seizures now
- B: Rare disabling seizures since surgery
- C: More than rare disabling seizures since surgery, but rare seizures for the last 2 years
- D: Nocturnal seizures only

**Class III: Worthwhile improvement†**
- A: Worthwhile seizure reduction
- B: Prolonged seizure-free intervals amounting to greater than half the followed-up period, but not less than 2 years

**Class IV: No worthwhile improvement**
- A: Significant seizure reduction
- B: No appreciable change
- C: Seizures worse

*Excludes early postoperative seizures (first few weeks).
†Determination of “worthwhile improvement” will require quantitative analysis of additional data such as percentage of seizure reduction, cognitive function, and quality of life.

of the dentate gyrus is usually seen (see EBRM, Volume 1, Part 3). There are varying degrees of involvement of the hippocampus. In more severe hippocampal sclerosis, mossy fiber sprouting can be identified in the dentate gyrus, in addition to granule cell dispersion and depletion in the dentate gyrus. Sclerosis is often found in the amygdala and in the parahippocampal gyrus as well.

The standard presurgical evaluation for patients with MTLE includes a careful history and physical examination. Ictal and interictal electroencephalography (EEG) and video-EEG with extracranial electrodes, magnetic resonance imaging (MRI) with specific sequences, and neuropsychological and neuropsychiatric assessment are also usually performed (see EBRM, Volume 1, Parts 2 and 3). Functional imaging with positron emission tomography (PET) or single-photon emission computed tomography (SPECT) is often utilized (see EBRM, Volume 1, Part 4). More invasive testing is considered, if needed. Historical details should include the age of seizure onset, presence of febrile seizures in early childhood, and any family history of epilepsy or unexplained deaths. Familial MTLE exists but is thought to be clinically and histopathologically indistinguishable from sporadic MTLE. There is currently no genetic determinant for predicting outcome after epilepsy surgery.

An accurate description of semiology, meaning the phenotype of the seizures, must be obtained, as the auras, automatisms, and postictal findings can help support the diagnosis of MTLE. For instance, 40% to 80% of patients with MTLE manifest aural or manual automatisms, include lip-smacking, chewing, and picking.

Ictal EEG recording is a major component of the preoperative evaluation for surgical consideration. Various ictal rhythms have been described, including background attenuation, start-stop-start phenomenon, irregular 2- to 5-Hz lateralized activity, and 5- to 10-Hz sinusoidal waves or repetitive epileptiform discharges. Postictal delta can be lateralized in 60% of patients with TLE and is concordant with the side of seizure onset in most patients. The standard scalp EEG electrode can detect up to 58% of all spikes. More invasive electrodes have been used to further evaluate seizure foci, and include sphenoidal, nasopharyngeal, anterior temporal, and surface electrodes overlying the mandibular notch or zygoma. If surface EEG yields inconclusive results, intracranial electrodes using subdural or intracerebral depth electrodes can be used to improve diagnostic accuracy (see EBRM, Volume 1, Part 2). No prospective studies have yet established the minimum number of ictal recordings necessary to prove lateralization and localization of seizure-onset zone. However, Sirven and colleagues reported that among a group of patients with bilateral seizure foci, all patients demonstrated contralateral seizure onset by the fourth recorded seizure. Blum used a statistical model to demonstrate that 5 recorded seizures were required to yield a 95% chance of avoiding a conflicting seizure, and only 4 seizures were required if all interictal spikes were noted to be unilateral.

In patients with medically refractory TLE, visualization of a lesion or evidence of mesial temporal sclerosis on MRI has been shown to be a prognostic indicator of good surgical outcome. MRI can suggest both the likely side of seizure onset as well as the probable surgical pathology, and therefore plays a critical role in the preoperative evaluation of patients. The widely accepted features of mesial temporal sclerosis on MRI include increased hippocampal signal intensity, reduced hippocampal volume, atrophy of hippocampal collateral white matter, enlarged temporal horn, reduced gray-
white matter demarcation in the temporal lobe, and decreased temporal lobe volume. Preoperative MRI evaluation should therefore include a T1-weighted volumetric acquisition allowing quantitative assessment of the hippocampal volume, T2-weighted coronal sequences, fluid-attenuated inversion recovery (FLAIR) images to detect increased signal in the hippocampus, and inversion recovery images to detect the loss of internal structure of the hippocampus (see EBRM, Volume 1, Part 3).

In addition to MRI, electroclinical correlation is recommended to confirm the epileptogenicity of the structural abnormality. There are 2 main types of surgically remediable TLE: MTLE and lateral or neocortical TLE. The latter may be unaccompanied by MRI findings but still benefit from surgical intervention. Immonen and colleagues found that 40% of 38 patients with MRI-negative TLE who underwent surgery achieved an Engel I seizure outcome (free of disabling seizures). Bell and colleagues reported that 60% of TLE patients with normal MRI achieved an Engel I surgical outcome. Therefore, patients with suspected “non-lesional” epilepsy based on MRI should not be denied access to a preoperative surgical evaluation.

In patients with normal MRI, greater emphasis is placed on ictal recordings and functional imaging, including PET and SPECT. Although the underlying pathophysiology has not been completely elucidated, a subset of these patients demonstrate lateralized temporal lobe seizures on ictal EEG, often with significant focal temporal hypometabolism on PET and yet normal MRI. In patients with hippocampal atrophy on MRI, PET typically reveals hypometabolism in the ipsilateral temporal lobe (see EBRM, Volume 1, Part 4). The presence of contralateral or bilateral temporal hypometabolism may suggest bilateral temporal lobe pathology with seizures arising independently from both hippocampi. Ictal SPECT is a useful adjunctive study in patients with negative MRIs and inconclusive EEGs. Studies have shown that if the radio-labeled tracer injection is given within 30 seconds of seizure onset, hyperperfusion can be identified at the site of the seizure focus in more than 90% of patients (see EBRM Volume 1, Part 4). The sensitivity of interictal SPECT drops to nearly 50%, and therefore this study is not very useful in localizing seizure focus.

**Surgical Procedure**

For many years, standard anterior temporal lobe resection was the most frequently used procedure for TLE. Several variants of this procedure have evolved, including a transcortical amygdalohippocampectomy as well as a trans-Sylvian amygdalohippocampectomy. The rationale for these variants includes relative sparing of temporal neocortex, with the potential benefit to postoperative language and cognitive function that this relative tissue sparing might provide. Once surgical intervention is selected, the surgical procedure generally involves the use of intraoperative image guidance, which helps in the planning of positioning and the surgical approach. The surgery itself can be performed using general endotracheal anesthesia or awake if there is concern about language function. It is worth emphasizing that language representation in the dominant hemisphere can vary substantially in patients who have had epilepsy from an early age. With an awake, cooperative patient, cortical mapping using electrical stimulation can be performed intraoperatively to confirm the location of language areas, using complex protocols to assure patient electrical safety and adequacy of functional mapping.
Resection of the temporal lobe typically extends approximately 6 to 6.5 cm posterior to the temporal pole on the nondominant side and 4.5 cm in the dominant temporal lobe (Figure 1). Hippocampal resection generally terminates posteriorly at the level of the tectal plate. Extent of resection should be confirmed on postoperative MRI. Amygdalohippocampectomy can avoid resection of temporal lobe neocortex, or amygdalohippocampectomy may be combined with resection of neocortex of the anterior temporal pole, leaving large lateral and inferior portions of temporal neocortex intact (Figure 2). Some groups tailor their hippocampal resection based on intraoperative electrocorticography of this structure. Presumably, amygdalohippocampectomy will reduce the likelihood of iatrogenic language and other deficits due to neocortical injury, although this expectation has not been confirmed by a randomized prospective trial of amygdalohippocampectomy versus “full” temporal lobectomy with margins tailored to exclude eloquent cortex that has been mapped with direct cortical electrical stimulation at the time of surgery.

Although anterior temporal lobectomy is considered the intervention of choice for intractable MTLE, radiosurgery targeting the mesial structures is an attractive option given its noninvasive nature, and has been the focus of much recent work. A drawback of radiosurgery is the lack of immediate seizure control—an average of 10 to 12 months is required until maximum seizure freedom is achieved. Post-procedural cerebral edema
has been documented, and this can require an extended duration of steroid therapy. The multicenter National Institutes of Health–funded Radiosurgery or Open Surgery for Epilepsy (ROSE) trial was recently closed due to lack of enrollment, but ongoing analysis of the accumulated results of this study might further elucidate the efficacy of radiosurgery in this patient population.

Risks of Surgery

In addition to the standard risks of a craniotomy, postoperative amnesia is a specific risk of temporal lobe surgery. Formal neuropsychological testing is used to provide a baseline assessment of cognitive functioning across all domains, to assess the risk of postoperative memory loss, and to help with localizing seizure focus by identifying the laterality of specific deficits in memory or other cognitive function. In patients with both verbal and nonverbal deficits, or with deficits ascribed to the side contralateral to the proposed side of surgery, an intracarotid amobarbital procedure (or “Wada test”) is used to establish language lateralization and whether the contralateral temporal lobe will be capable of sustaining memory function postoperatively. Studies examining the use of the Wada test for presurgical evaluation show wide variations in the use of the test, with 25% to 35% of all surgical patients undergoing Wada testing. The lack of more widespread use of preoperative Wada testing is in part due to its requirement for invasive cerebral angiography, which carries a risk of stroke (up to 10% in some centers) and other complications. For this reason, much interest has centered on the use of noninvasive techniques such as language-activation functional MRI, but to date no noninvasive technique for language lateralization has supplanted Wada testing in terms of accuracy.

From an anatomical standpoint, visual pathway fibers are located in the roof of the temporal horn as they extend forward from the lateral geniculate...
body before turning posterior to reach the calcarine cortex. Since the location of these fibers is not always predictable, standard anterior temporal resections can result in a “pie in the sky” superior quadrantanopsia in the contralateral visual field. This postoperative deficit has been documented in 35% to 50% of patients undergoing surgery for MTLE.57 Worsened or new postoperative memory problems are expected in 1% to 4% of patients.58–60 Preoperative risk factors for decreased memory function following surgery include dominant TLE, lack of hippocampal sclerosis on MRI or histopathology, normal baseline neuropsychological functioning, and later age of seizure onset. Postoperative hemiparesis occurred in 2% to 5% of patients,59 and is a consequence of anterior cho-roidal artery injury or direct injury to the cerebral peduncle, which lies medial to the hippocampus. Other series report much lower rates of hemipa-

Seizure Outcome and Overall Outcome

Despite the risks of surgery, surgical therapy for mesial temporal sclerosis has been demonstrated to be superior to optimal medical therapy. Evaluation of outcome is based on seizure frequency, cognitive outcome, and quality-of-life measures. Wiebe and colleagues in 2001 reported the results of their prospective trial of 80 patients randomly assigned to receive either temporal lobectomy or optimal medical therapy.61 The proportion of patients who were free of seizures impairing awareness at 1 year was 58% in the surgical group and only 8% in the best-medical-therapy group ($P < 0.001$). The proportion of patients who were free of all seizures, including aura, was 38% in the surgical group and 3% in the medical group ($P < 0.001$).61 Quality of life was also shown to be better in the surgical group at both 6 months and 1 year following surgery. There was no difference in psychiatric comorbidities between the 2 groups. Psychopathology and depression were assessed using the General Health Questionnaire and the depression scale of the Center for Epidemiological Studies, respectively. All of these instruments have demonstrated reliability and validity in assessing patients with epilepsy and were self-administered at baseline and at 3, 6, 9, and 12 months. Four patients had adverse effects from surgery. A small thalamic infarct developed in 1 patient, causing sensory abnormalities in the left thigh; in 2 patients, there was a decline in verbal memory that interfered with the patients’ occupations at 1 year. Asymptomatic, superior subquadrantic visual-field defects occurred in 22 patients in the surgical group (55%), as expected. No neurologic abnormalities occurred in the patients in the medical group. Depression occurred in 7 patients in the surgical group (18%) and 8 patients in the medical group (20%). Transient psychosis developed in 1 patient in each group. These findings strongly support the use of anterior temporal lobectomy over best medical therapy alone for the treatment of MTLE.

The Early Randomized Surgical Epilepsy Trial (ERSET) was a randomized, controlled clinical trial performed at 16 U.S. epilepsy surgery centers.62 The 38 MTLE patients had disabling seizures for less than 2 years, with adequate trials of 2 antiseizure medications. Participants were randomly assigned to ongoing trials of antiseizure drugs (medical group) or to temporal resection (surgical group), and seizures were followed for 2 years. None of 23 patients in the medical group became seizure-free after 2 years of further medication trials, but 11 of 15 in the surgical group were seizure-free during year 2 of follow-up ($P < 0.001$). The sample was
too small to permit definitive conclusions about treatment group differences in cognitive outcomes. Adverse events in the medical group included 3 cases of status epilepticus, and in the surgical group included a postoperative stroke with only transient neurologic deficit.

Systematic reviews of the current literature demonstrate that even after 5 years, the proportion of seizure-free patients is preserved.63,64 Recently, attention has been paid to the seizure outcome in patients who do not become entirely seizure-free after surgery. Most such patients experience major overall seizure reduction, although in some instances the reduction in complex partial seizures is greater than the relative reduction in grand mal seizures.65,66 A more common outcome pattern is to become free of seizures that cause impaired awareness but to continue to experience isolated auras, often with aura symptoms that are similar in preoperative and postoperative periods.67 The overall effects of amygalohippocampectomy with regard to seizure freedom and semiological alterations during seizures that recur after surgery appear rather similar to those of anterior temporal lobectomy.68

**CORTICECTOMY AND CEREBRAL LESIONECTOMY**

**Evaluation**

In approaching refractory epilepsies with features of neocortical (non-limbic system) seizures, localization of the cortex with earliest ictal discharges may in some cases be sufficient to direct surgery in the absence of a cerebral lesion. In general, the localization process is more likely to be successful and the outcome of resection to be efficacious in controlling seizures when a causative lesion is imaged with MRI.69–71 It is often quite difficult to localize ictal onset zones in frontal lobe limbic structures such as the insula and orbitofrontal and cingulate cortices in the absence of a lesion imaged on MRI, but subdural and intracerebral (depth) electrodes can be used to do so.72,73 Neocortical ictal onset zones on the dorsolateral surfaces of the cerebral hemispheres are readily studied with subdural grid arrays, which also support functional mapping by direct cortical electrical stimulation (as reviewed in EBRM, Volume 1 Part 217). The anatomical outcome of corticectomy is readily evaluated with MRI (Figure 3).

Certain types of intracranial lesions are more likely to be epileptogenic, particularly those involv-
ing exposure of cortex to hemosiderin or calcium (see EBRM, Volume 1, Part 3\textsuperscript{15}). Such lesions include neoplasms (eg, astrocytoma, ganglioglioma, pleomorphic xanthoastrocytoma, and dysembryoplastic neuroepithelial tumor), vascular lesions (eg, cavernous hemangioma and arteriovenous malformation), and dysgenetic lesions (eg, microdysgenesis, focal or diffuse dysplasia, Sturge-Weber syndrome, and tuberous sclerosis), or may be traumatic/ischemic in nature. Why lesions cause seizures is unknown, but seizures might occur as a consequence of synaptic reorganization or changes in extracellular ion concentration, inhibitory interneurons, intrinsic neuronal channels, or expression of gap junctions; or they may occur due to vascular changes or hemosiderin deposition, or in GABA or NMDA channels.

Although advances in structural and functional MRI have allowed for identification of more subtle lesions, 20% to 30% of patients with temporal epilepsy and 20% to 40% of those with extratemporal epilepsy have no clear lesion on currently available clinical MRI.\textsuperscript{74–76} Nonlesional, refractory partial epilepsies appear to be more common among frontal lobe epilepsies than in TLE.

**Seizure Outcome**

The highest rate of seizure reduction has been reported when there is congruence between the location of the lesion on MRI and the location of the seizure focus on EEG. Overall, electrophysiologically guided corticectomy in the absence of an associated MRI-defined lesion results in full seizure control in 20% to 50% of cases, while electrophysiologically guided corticectomy coupled with resection of an associated lesion offers full seizure control in 50% to 80% of cases, in review of multiple series.\textsuperscript{69–71} The surgical approach in such patients is then one of removing the lesion if one is present, and also the electrophysiologically defined seizure-onset zone. A recent meta-analysis by Tellez-Zenteno and colleagues\textsuperscript{77} demonstrated that the odds of being seizure-free 1 year or later after epilepsy surgery were 2.5 to 2.8 times higher in patients with a lesion identified by MRI or histopathology. Certain lesions, including cavernous malformations and small focal dysplasias, appear to offer higher rates of full seizure control with corticectomy-lesionectomy, while large and incompletely resected malformations of cortical development and glial neoplasia are associated with lower rates of postresective seizure control.\textsuperscript{78–82}

**CORPUS CALLOSOTOMY FOR EPILEPTIC DROP ATTACKS IN SYMPTOMATIC GENERALIZED EPILEPSIES**

Seizure generalization requires bilateral synchrony and spread through subcortical structures, including the corpus callosum. Subtotal or staged total corpus callosotomy is used as a palliative treatment in patients with generalized tonic-clonic seizures and unresectable seizure foci and drop attacks. Drop attacks are caused by tonic or atonic seizures and can result in significant injury due to falls.

**Seizure Outcomes and Risks of Surgery**

Callosotomy is considered palliative, as resulting rates of complete seizure freedom are low. The main goals of callosotomy are to alleviate seizure severity and to eliminate drop attacks. Various studies support the finding that callosotomy results are best in patients with generalized tonic-clonic seizures and drop attacks.\textsuperscript{83–90} The relapse rate for drop attacks is low, especially following complete corpus callosotomy, with one study documenting a 13% relapse rate at 6 years after surgery.\textsuperscript{91} When
partial callosotomy was employed, 91% of patients were seizure-free at 1 year, but this dropped to 58% at 6 years. This decreased long-term efficacy of partial callosotomy has been illustrated several times.88,92,93

Complete initial corpus callosotomy engenders a higher risk of postoperative disconnection syndrome. Symptoms of disconnection syndrome include left tactile anomia, left-sided dyspraxia, pseudo-hemianopsia, right-sided anomia for smells, difficulty with right-hand spatial synthesis, decreased spontaneity of speech, and incontinence. For this reason, if a complete callosotomy is required for symptom control, it is generally staged by sectioning the anterior two-thirds first and later doing the posterior third. If patients develop disconnection syndrome after partial callosotomy, it can resolve in a few days, but sometimes requires up to 2 to 3 months for resolution.94 Although the actual incidence is unknown, disconnection syndrome can be permanent in those who undergo total callosotomy. This outcome is less likely with a staged procedure, however.95

Lennox-Gastaut syndrome is one form of epilepsy that responds favorably to corpus callosotomy. This syndrome usually begins between the ages of 1 and 8 years, and persists into adulthood. It is refractory to antiepileptic medications and results in cognitive decline and behavioral problems in affected individuals. The most common seizure pattern in these patients is nocturnal tonic seizures, but others include axial tonic, atonic, atypical absence, and myoclonic seizures. The syndrome is known to result from intrauterine infections and vascular injury to the brain, but can also be cryptogenic in origin. The pathological basis seems to include neuronal migrational abnormalities and late effects of central nervous system infection. EEG usually demonstrates high-voltage, bifrontal 1.5- to 2.5-Hz spike-and-wave complexes interictally and attenuation with paroxysmal fast activity from 10 to 13 Hz during the ictal phase.96

**Surgical Procedure**

Modern corpus callosotomy is done with the aid of a neuronavigational guidance system. The approach is generally from the nondominant side for language, with care taken to preserve the superior sagittal sinus and large draining veins during dural incision and cerebral retraction in order to avoid significant venous infarct. Callosal sectioning is usually carried out from the posterior margin of the callosotomy to the anterior margin. The posterior border of resection typically lies within 5 cm of the callosal genu. In complete callosotomy, visualization of arachnoid covering the vein of Galen and internal cerebral veins establishes the posterior edge of resection.97

**MULTIPLE SUBPIAL TRANSECTION FOR NEOCORTICAL EPILEPSIES**

When the seizure-onset zone is situated partly or wholly in eloquent cortex, total lesionectomy is not possible given the likelihood of postoperative neurological deficits. The technique of multiple subpial transections (MSTs) was therefore developed as an option for epileptogenic lesions that are situated in eloquent cortex. Neuroanatomical studies have shown that the basic functional cortical unit is arranged vertically, whereas epileptic activity spreads horizontally through the cortex. From a theoretical basis, therefore, vertical incisions in the cortex can be expected to interrupt transverse synaptic connections, preventing seizures from propagating while preserving the vertical column that is critical to neuronal function. Because a minimal contiguous cortical surface area is neces-
Multiple subpial transections seem to be effective in language recovery for these patients. There is an observed long-term recurrence rate of nearly 20% in patients who initially have a postoperative improvement. For this reason, MSTs are generally reserved for patients in whom seizures are refractory and primary lesionectomy cannot be performed because the lesion is situated in eloquent cortex.

**Surgical Procedure**

The initial procedure was described by Morrell in 1989, and although there have been some small variations in the technique, the concept remains the same as when initially described (Figure 4). The location of the area of interest is identified by cortical stimulation and electrocorticography prior to the start of the procedure. A fine wire with a 4- to 5-mm up-angled tip is used to puncture the cortex. Transections are placed 5 mm from each other and electrocorticography is performed intraoperatively to check for residual significant spiking, in which case further transections are carried out.

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