In recent years, as new neuroimaging techniques have revealed hippocampal sclerosis, focal cortical dysplasia, and other subtle epileptogenic lesions, the use of chronically implanted invasive electrodes has decreased at many epilepsy surgery centers. The risks of invasive electrodes are not warranted when magnetic resonance imaging (MRI) and extracranial electroencephalography (EEG) disclose concordant evidence of an epileptogenic zone in a safely resectable area. Neuroimaging is now so advanced that the majority of patients who undergo resective epilepsy surgery do not require invasive EEG studies. In some cases, however, invasive techniques remain important because of discordant or poorly defined results from noninvasive testing or close proximity of the epileptogenic zone to eloquent cortex.

EXTRACRANIAL ELECTROENCEPHALOGRAPHY: THE STARTING POINT

The questions to be answered with intracranial electrodes are shaped by the results of the noninvasive evaluation, including extracranial EEG (1–3). Ideal for the initial identification of a suspected region of epileptogenesis, extracranial EEG provides a broad survey of EEG rhythms throughout both hemispheres and should be designed to yield the maximum localizing information about the epileptogenic zone (3). Sphenoidal electrodes (Fig. 77.1) may be helpful when mesial temporal lobe epilepsy is suspected. Generally, surface EEG-video monitoring is the initial test for any patient with frequent seizures despite medications, as 20% to 30% of adults will turn out to have psychogenic seizures (see Chapter 42).

The main limitation of extracranial EEG is decreased sensitivity to cortical generators (4,5). Intracranial electrodes overcome the sensitivity limitations of extracranial electrodes because they are closer to the cortical focus and free of the dampening effect of the skull and scalp. This increased sensitivity, however, is at the expense of more restricted sampling, or "vision," and involves an enhanced risk of complications.

Intracranial EEG may fail to define further the epileptogenic zone if problem areas are insufficiently covered, but the use of large numbers of electrodes is limited by the proportional increase in the rate of complications. For this reason, intracranial electrodes should be used only after noninvasive testing (i.e., EEG, video semiology, and imaging) has "narrowed down" the epileptogenic zone to a limited brain region that can be covered safely and adequately by the chosen invasive technique.

The strength of the hypothesis based on the results of the noninvasive evaluation is a key to successful use of invasive techniques. The clearer the question formulated for testing, the greater the chance of success with the invasive evaluation.

This chapter provides an overview of the invasive techniques available for these difficult cases and reviews the major clinical situations and how they can be approached.

INTRACRANIAL ELECTRODES: AN OVERVIEW

Depth and subdural electrodes are the most commonly used intracranial electrodes. Because of limited sensitivity, foramen ovale and epidural peg electrodes are rarely or no longer placed.
DEPTH ELECTRODES

Surgical Aspects

Depth electrodes are multiple-contact “needles” of polyurethane or other material that typically are inserted into the brain by way of twist-drill skull holes under stereotactic guidance (6–8). Modern computer-assisted image-based stereotaxy has greatly improved the ease and precision of depth electrode placement. A target is chosen on the MRI scan, and entry point, trajectory, and depth are calculated by the computer to result in precise placement of the electrode tip within 1 mm of the target.

A common approach for patients with suspected bitemporal epilepsy uses three electrodes, each with eight contacts that are advanced transversely through punctures in the middle or inferior temporal gyri into the amygdala and anterior and posterior hippocampus on each side (Fig. 77.2). These allow the survey of electrical activity from the mesial structures, from infolded gray matter of basal temporal gyri, and from the lateral temporal lobe.

An alternative trajectory for the evaluation of mesial temporal epilepsy is the longitudinal placement of depth electrodes by way of occipital burr holes (8–10). With this approach, the electrode traverses the course of the hippocampus along its axis, sampling electrical activity throughout its length. Extratemporal foci are surveyed by carefully locating the electrodes according to structural lesions or particular gyri with suspected involvement in the epileptogenic zone (11).

Depth electrodes may be placed under local or general anesthesia, with the latter preferred for lengthy procedures involving multiple insertions, and can be removed under local anesthesia. Previous insertion of depth electrodes does not significantly limit further options of epilepsy surgery, including the subsequent use of other electrode types.

Advantages

The main advantage is direct access to deep structures for EEG recording very close to potential generators (12–14). Electrodes can be left in place for days to weeks with minimal risk of infection, permitting extensive ictal recording. Ictal EEG onset with depth electrodes often precedes onset with scalp and sphenoidal electrodes by 20 or 30 seconds, and in some cases, especially auras (“simple partial seizures”), the EEG seizure pattern may be seen only with depth recording. Depth electrodes may clearly locate seizure onset when extracranial localization is unclear. In addition to seizure onset, seizure termination may also have localizing and prognostic value, with unilateral termination...
(as opposed to simultaneous bilateral, contralateral, or mixed termination) predicting better outcome after temporal lobectomy (15).

**Disadvantages**

Depth electrodes sample only a relatively small brain region, providing a very detailed but also very focused EEG sample. This focus may be inadequate when the issue is localization of seizure onset within a relatively large region such as the frontal lobe.

In addition, placement requires brain penetration. This raises theoretical concerns about damage to cortical areas outside the resection site and also makes depth electrodes inappropriate for the study of potential epileptogenic foci near vascular malformations. The examination of resected tissues has revealed gliosis, cystic degeneration, or microcysts along the tracks of depth electrodes, but several studies (10) have failed to demonstrate any functional sequelae in the absence of clinically apparent bleeding or infection, and overall depth electrodes are safe (16).

The risk of bleeding or infection is only 0.5% to 5% (12,17). Routine imaging studies commonly reveal asymptomatic subdural collections of blood, but intraparenchymal hemorrhage is very rare [less than 1% in series (7,10) using modern stereotactic techniques]. The risk of significant hemorrhage is decreased by careful attention to electrode trajectories on preoperative planning studies so as to avoid major vascular structures.

**SUBDURAL ELECTRODES (GRIDS AND STRIPS)**

**Surgical Aspects**

Probably the most commonly used invasive electrodes, subdural electrodes are embedded in strips or sheets of polyurethane or other material and may be implanted subdurally over epileptogenic regions (Fig. 77.3) (18–25). These discs of stainless steel or platinum alloy, approximately 2 to 4 mm in diameter, are embedded in polyurethane at fixed interelectrode distances, typically 10 mm, in various arrays. The strips and grids include one or more cables with bundled insulated wires connecting to the individual electrodes. Cables can be connected by means of various interface blocks to conventional EEG equipment for recording and stimulation. Other subdural grids have been designed with electrode contacts on both sides of the polyurethane sheet for recording from both surfaces, as in interhemispheric locations.

Strips can be inserted under fluoroscopic guidance through individual burr holes or trephines for bilateral placement when the side of seizure onset must be determined. The cables exit through a stab wound separate from the main incision to assist with anchoring of the strip and to decrease cerebrospinal fluid leakage and infection. Subdural strips may be placed under local or general anesthesia, although general anesthesia is preferred for multiple burr holes and multiple strip insertions. The risk of infection and hemorrhage with insertion of subdural strips has been reported to be less than 1% (9,21). Because mobility of implanted subdural strips may change the position of electrodes in relation to the intended recording target, serial skull roentgenograms should be performed to verify stability of position.

Grids are inserted by way of open craniotomy (Fig. 77.4). Flap design allows coverage of all regions of suspected epileptogenicity and subsequent access to any possible resection to the region of interest. Subdural plates may be “slid” beyond the edges of the craniotomy to cover adjacent areas, including basal temporal, basal frontal, and interhemispheric regions. Subdural grids are sutured to the overlying dura mater to prevent movement. A watertight dural closure around the electrode cables lessens the possibility of cerebrospinal fluid leakage. Whenever feasible, the overlying bone flap should be osteoplastic (attached to a vascularized muscle and periosteal pedicle) to prevent flap osteomyelitis. The electrode cable exits through a stab wound separate from the main incision, and watertight sutures are used at the exit site to reduce cerebrospinal fluid leakage. Despite these precautions, minor leakage frequently occurs without serious complications.

After completion of the evaluation with subdural electrodes, the patient is returned to the operating room for reopening of the craniotomy, removal of the subdural electrodes, and final resection of the mapped epileptogenic zone. This second operation typically is performed using general anesthesia, although local anesthesia is an option when further brain mapping is necessary. At reoperation, cultures are obtained from all layers of the wound, all electrode hardware, and the bone flap. If bacterial colonization of one or more wound layers is observed, the patient receives vigorous intravenous antibiotic therapy directed against the cultured organism(s) for two weeks following removal of the electrodes to reduce the risk of flap osteomyelitis.

With an overall rate of 26%, subdural grids present the greatest potential for complications (26). These include infection (12%), transient neurologic deficit (11%), epidural hematoma (2.5%), increased intracranial pressure (2.5%), infarction (1.5%), and death (0.5%). The occurrence of complications is associated with large numbers of grids/electrodes (more than 60 electrodes), lengthy monitoring (more than 10 days), older age, left-sided grid insertion, and burr holes in addition to the craniotomy. Improvements in grid technology, surgical technique, and postoperative care may reduce the rate of complications (26–28).

**Functional Localization Studies**

Functional localization techniques with subdural electrodes include cortical stimulation and evoked potential...
Cortical stimulation involves passage of a small electrical current through individual electrodes, with close observation for symptoms or interference with cortical function (20, 29). An alternating current is applied for 5 to 10 seconds, with subsequent stepwise advancement from 1 mA to a maximum of 15 mA or until symptoms or after-discharges on EEG develop. Symptoms during stimulation may include positive motor phenomena (tonic or clonic contraction of a muscle group), negative motor phenomena (inhibition of voluntary movements of the tongue, fingers, or toes), somatosensory phenomena (tingling, tightness, or numbness of a part of the body), or language impairment (speech hesitation or arrest, anomia, or receptive difficulties). To screen for negative motor or language impairment during stimulation, the patient may be challenged to read or perform rapid alternating movements of the fingers, toes, or tongue. Signs or symptoms during stimulation of an electrode are interpreted to mean that the underlying cortex has importance for the affected function. In addition to mapping eloquent cortex, stimulation may also help to localize epileptogenic cortex. After single pulse stimulation, “early responses” (starting within 100 ms) are found in all areas of cortex. Delayed responses (spikes or sharp waves occurring between 100 ms and 1 second after stimulation) appear to be significantly associated with the epileptogenic zone (30).

Figure 77.3  Results of electroencephalography (EEG) and cortical stimulation with subdural electrode grids. With scalp and sphenoidal EEG, this patient had epileptiform discharges from the anterior and posterior left temporal lobe. Extraoperative subdural EEG showed interictal sharp waves from anterolateral, posterolateral, and basal temporal areas. Seizures arose from anterior and basal temporal regions. The posterior temporal area with interictal sharp waves was within Wernicke language area, so this region was left untouched by the extensive left temporal lobectomy. Resection extended 7.5 cm posteriorly from the anterior temporal tip. Histopathologic examination of resected tissue showed cortical dysplasia; the magnetic resonance imaging techniques at that time were not adequate to reveal the subtle malformation. The patient remains seizure free on medication 12 years after surgery but has had seizures when medications were withdrawn.
Advantages

Subdural electrodes permit detailed definition of the epileptogenic zone in relation to eloquent cortex. Epileptiform discharges may be recorded during wakefulness, sleep, and seizures and then mapped (20) to define the safest, most complete resection of epileptogenic zones (24,25). Ictal EEG patterns are usually well defined if electrodes are over the epileptogenic zone. At least for temporal lobe seizures, the time from EEG onset to clinical onset may have a prognostic value (31). Subdural electrodes can be visualized on and combined with imaging in order to localize EEG findings with respect to normal anatomy or lesions (Fig. 77.5).

In another method of functional localization (32), median or posterior tibial evoked potentials may be recorded directly from the cortical surface by means of subdural electrodes, with maximum amplitudes over the postcentral gyrus. Results may confirm rolandic sensorimotor localization by cortical stimulation.

In infants and young children, cortical stimulation studies are more challenging. Sensory, negative motor, and language function cannot be assessed reliably during stimulation in infants. Special stimulation paradigms are required to elicit positive motor effects in children younger than three or four years (32,33). Evoked potential studies with subdural electrodes may help to identify the postcentral gyrus at any age.

Disadvantages

The risks of wound infection and flap osteomyelitis are the main disadvantages of chronically implanted subdural
electrode grids. The incidence of 5% to 15% (24,25) about a decade ago has decreased in recent years, but occasional infections have occurred despite compulsive intraoperative culturing of all wound layers and vigorous prophylactic use of antibiotics. Infection may be less frequent with subdural strips (22,33) than with grids.

Other complications of subdural electrodes—acute meningitis, cerebral edema, and hemorrhage—are rare. Meningitis necessitates immediate electrode removal and vigorous antibiotic therapy. Brain edema can, rarely, be symptomatic, requiring early removal of electrodes, but usually it can be successfully combated with judicious fluid and electrolyte management. Occurring in approximately 2% of patients (19), subdural or epidural hemorrhage may prompt premature removal of electrodes and evacuation of hemorrhage.

Concerns about intracranial pressure limit the number of subdural electrodes, so that only restricted unilateral cortical areas can be covered with grids. Strips can cover widespread areas through multiple burr holes, but mobility of the strips can be a problem and blind insertion of the strips may be impeded by subdural scarring or other structural lesions.

NEW OR INVESTIGATIONAL TECHNIQUES

Intraventricular Electrodes

In this newly proposed technique, frameless image guidance can be used to place a 10-contact depth electrode through a rigid neuroendoscope within the atrium of the lateral ventricle. Invasiveness is lessened and complications may be fewer than with transcortical depth electrode placement (34,35).

Cavernous Sinus Electrodes

This newer semi-invasive technique may be useful for lateralization of temporal lobe epilepsy (36,37). Wire electrodes can be placed in the cavernous sinus and the superior petrosal sinus by way of the jugular vein.

INTRAOPERATIVE ELECTROCORTICOGRAPHY AND FUNCTIONAL MAPPING

Surgical Aspects

Intraoperative electrocorticography (ECoG), the recording from electrodes laid directly over exposed cortex after craniotomy (29,38–40), can be performed with the patient under either local anesthesia (fully awake) or general anesthesia. Because general anesthetic agents may affect ECoG, all inhalation agents are discontinued approximately 30 minutes before the recording. Paralytic agents, nitrous oxide, and intravenous narcotics are continued to maintain manageable general anesthesia without potential effects of inhalation agents.

Intraoperative ECoG may (occasionally) include the recording of evoked potentials to localize the rolandic fissure and orient the surgeon toward gyral anatomy so as to avoid resections in functional motor or sensory areas. Interictal epileptiform activity can be recorded for a stated period to define a zone of frequent interictal spiking, thereby helping the surgeon tailor the resection for maximal excision of these areas. Surgical manipulation itself, however, may create some spike activity ("injury spikes"), and the practice of "chasing spikes" to maximize resection has not been shown convincingly to improve the outcome of resective epilepsy procedures. Most investigators have found that spikes on postresection ECoG do not reliably predict a less favorable outcome in temporal lobe resections (24,41–47). Preexcision spikes on three or more gyri that persist after resection, especially at a distance from the resection border, carry a poor prognosis, at least in nontumoral frontal lobe epilepsy (47).

Intraoperative cortical stimulation can delineate areas of primary motor, sensory, and speech function with the patient under local anesthesia. Even with light general anesthesia (without paralytic agents), this technique can reliably identify primary motor areas by allowing direct observation of clonic or tonic movement in respective muscle groups and facilitating tailored resections close to motor regions (39).

Advantages

Intraoperative techniques permit definition of functional cortex in relation to the epileptogenic zone while avoiding the potential complications of long-term invasive electrodes. The procedure lengthens the operating time but otherwise imparts no added risk to the patient. Detailed intraoperative cortical stimulation under local anesthesia is readily performed in cooperative adolescents and adults (40) but is more difficult in young children or uncooperative adults. Even in young or difficult patients, however, it is usually possible to identify primary motor cortex intraoperatively with cortical stimulation and evoked potential studies using light general anesthesia (48).

Disadvantages

Because the total recording time of intraoperative techniques is limited to a few hours, recording during seizures is almost never obtained. Another limitation to intraoperative techniques is the stressful nature of the conditions for cortical stimulation while the patient is awake.
INDICATIONS AND CLINICAL USE

Suspected Bilateral Mesial Temporal Lobe Epilepsy

The need for invasive EEG in temporal lobe epilepsy has diminished as more powerful MRI has enhanced identification of hippocampal pathology. Nevertheless, bilateral mesial temporal lobe epilepsy is the most common indication for depth electrodes implanted into the amygdala and anterior and posterior hippocampus on both sides (8,14,49,50).

Bitemporal strips may also be used in this setting. Some authors (43) have found that subdural and depth electrodes are comparably sensitive for detection of interictal spikes in both mesial and neocortical temporal lobe epilepsy. Depth electrodes, however, are the only ones to lie within the mesial epileptogenic cortex and thus may better allow detection of mesial-onset seizures than do subdural strips, which can reach only the parahippocampal gyrus (51,52). For example, studies that used both methods simultaneously reported cases in which bitemporal strips failed to provide adequate information to proceed with surgery (52–54). Occasionally, subdural strips can even be falsely lateralizing (55). Only depth electrodes reliably record faster frequencies at onset (56,57), suggesting closer proximity to the generator. Although depth electrodes probably remain the gold standard for recording hippocampal onset, subdural strips are probably adequate when the issue is only lateralization of temporal lobe epilepsy (58). When extratemporal onset is a concern (e.g., in the setting of an extratemporal lesion of uncertain relevance), a combination of depth and subdural electrodes is appropriate (9,11,59).

Epileptogenic Zone Near Eloquent Cortex

Subdural electrodes are the method of choice whenever eloquent cortex must be clearly separated from the epileptogenic zone. For example, subdural electrodes may be used to define a frontal or parietal focus in relation to Rolandic sensorimotor areas, a left lateral temporal focus in relation to Wernicke’s language area, or a mesial frontal or parietal focus in relation to the supplementary motor area and primary motor cortex for the leg.

Although either extraoperative or intraoperative techniques can be used to resolve such localization problems, the considerable variability in preferred methods depends largely on the familiarity of the surgery team with each approach. In general, intraoperative techniques may be preferable when the primary objective is localization of Rolandic motor areas, for example, in preparation for anatomic frontal lobectomy or lesionectomy. In fact, intraoperative mapping is often used before resection in patients without seizures. Extraoperative techniques may be preferable if ictal recording is required to define the epileptogenic zone. The two techniques can also be combined, with extraoperative seizure recording followed by intraoperative mapping just before resection.

Poor Localization of Epileptogenic Zone

Hemisphere Known but Exact Localization Uncertain

Relatively often, the results of the noninvasive evaluation unequivocally point to a hemisphere, but the lobe cannot be confidently identified. In these patients, prognosis for surgical outcome is typically guarded, but an attempt to better define the epileptogenic zone with invasive techniques may be appropriate in some patients, and outcome can be excellent (60). Because this requires coverage of large areas on one side, grids can be combined with strips or depth electrodes. Depth EEG has been used, with good results, to resolve other discrete localization issues such as mesial temporal versus orbitofrontal or cingulate seizure onset. In these cases, depth and subdural electrodes may be used together (53,59), especially for a presumed extratemporal onset, such as orbitofrontal (9) or occipital (11).

In the presence of a lesion apparent on MRI, even such subtle anomalies as a suspected cortical dysplasia, invasive EEG may not be necessary (61). However, any lesion should not be assumed to be the source of the seizures (“dual pathology”), as some lesions are often incidental (e.g., arachnoid cysts). If an extratemporal lesion is present but electroclinical data (EEG-video) suggest temporal onset, or if MRI evidence supports mesiotemporal sclerosis but electroclinical data suggest extratemporal onset, then invasive EEG (strips or grids) is needed.

Lobar Localization Known but Side Uncertain

Although most cases of extratemporal onset involve difficult intrahemispheric localization, lateralization is occasionally at issue. This is particularly common in seizures arising from the supplementary sensorimotor area, where symptomatic and midline epileptiform discharges indicate mesial frontal onset, but lateralization is unclear in the absence of imaging abnormalities or clinical lateralizing signs (62). These highly challenging cases may be difficult to clarify even with invasive EEG.

When the noninvasive presurgical evaluation does not sufficiently narrow the possibilities for localization, invasive studies may be of limited benefit.

CONCLUSIONS

With the advent of modern neuroimaging, the use of invasive electrodes has diminished. Presurgical evaluation in patients with localization-related epilepsy remains variable and controversial. No universal scheme is accepted by all
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epilepsy surgery centers. Techniques improve, and strategic approaches continue to evolve (63). In each case, the decisions whether or not to use an invasive technique and, if so, which one should be based on results of an extensive noninvasive evaluation including extracranial EEG, video and seizure semiology analysis, structural and functional neuroimaging, and neuropsychological testing. Appreciating the brain coverage, strengths, and weaknesses of each invasive technique will help in this choice. In addition, the risk of invasive techniques varies among surgeons; as with other types of surgical procedures, experience and successful practice are important. The lowest complication rates can be expected from experienced epilepsy neurosurgeons at high-volume epilepsy surgery centers.

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REFERENCES


