# Seizures and Epilepsy: Electrophysiological Diagnosis

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INTRODUCTION

Electroencephalography (EEG) and video-EEG are powerful tools in the diagnosis of seizures and epilepsy. While EEG and derived techniques have considerable utility in nervous system conditions other than epilepsy, the most frequent and essential indications for EEG are in seizures and epilepsy. The fully educated adult or pediatric epileptologist usually is also a fully trained EEG expert. This review presumes considerable background in both epileptology and clinical neurophysiology.

In the clinic or hospital, the cognitively flexible EEG-epilepsy expert will be able to move from a differential diagnosis of paroxysmal clinical events reported for a patient he or she has seen, to selection of an appropriate EEG procedure, then to interpretation of the interictal and ictal EEG, and on to application of the findings to diagnosis of that patient. In the clinical neurophysiology laboratory, the cognitively flexible EEG-epilepsy expert will be able to interpret an interictal or ictal EEG of a patient she or he has never seen and generate a differential diagnosis of possible clinical correlates of the spikes or other recorded abnormalities. Part 1 of this series reviewed the epilepsy syndromes, with summaries of typical EEG findings in particular syndromes (“syndromes-to-electrophysiology” associations). The core of this article reviews particular interictal and ictal EEG findings, with illustration of typical examples, discussion of diagnostic difficulties, and review of clinical associations (“electrophysiology-to-syndromes” associations).

Generation of the human EEG is discussed with emphasis on the clinical utility and limitations of extracranial and intracranial EEG recordings. We note limitations posed by artifacts and complexities posed by nonpathological sharply contoured or rhythmic EEG potentials. We also discuss specialized EEG techniques used in presurgical epilepsy evaluations. This summary can be supplemented with review of the cited original papers and standard textbooks and EEG atlases.

GENERATION OF THE HUMAN EEG

The scalp EEG is a severely limited sampling of brain electrical activities. Nonetheless, scalp
EEG recordings are highly informative with regard to state of arousal and often to ictal and interictal abnormalities of diagnostic significance in the epilepsies. In general, brain electrical activities are generated by ionic currents in neurons and glia, which are regulated by neurotransmission and other biochemical processes. Cortical neurons generate electrical currents due to action potentials, excitatory and inhibitory postsynaptic potentials (EPSPs and IPSPs), and “intrinsic” membrane currents arising from voltage-dependent ion channels. Only the EPSPs and IPSPs in radially oriented apical dendrites of neocortical pyramidal neurons contribute significantly to generation of the scalp EEG, however. The location and orientation of synchronized dipolar cortical postsynaptic potentials (PSPs) are critical to detection by scalp EEG electrodes (Figure 1, Figure 2, and Figure 3). Figures 1, 2, and 3 illustrate some of the geometric effects of cortical anatomy that permit or prevent scalp EEG recording of potentials synchronized over surfaces larger than 6 cm². A highly focal field synchronized atop one gyral crest may be “blurred” into a larger scalp EEG distribution, in part because the scalp electrodes located away from the center of the gyral crest can detect its charge and also because intervening soft and boney tissues may conduct currents laterally. The limited spatial sampling of scalp electrodes and the low- and high-frequency filtering of the EEG machine also account, in part, for the exclusion of glial electrical potentials and neuronal action potential.

Figure 1. Two-dimensional schema of surface-negative event at gyral crest. Gloor’s schema shows that scalp potential P1 directly overlies a gyral crest that has overall major negativity, such that the solid angle (Ω₁⁻) supports recording of a strongly negative electrical potential at this site. A scalp electrode site lateral to this area also records a strongly negative electrical potential (Ω₂⁻), but its solid angles of sampling also “see” positive ends of dipoles at the undersurface of the cortical ribbon (Ω₂⁺). Overall, P1 is much more negative than P2, which will be quite well recorded at a channel comparing electrodes 1 and 2. (Adapted with permission from Gloor P. Contributions of electroencephalography and electrocorticography to the neurological treatment of the epilepsies. Adv Neurol 1975;8:59–105.)

Ω_{2eff} = \Omega_{-2} - \Omega_{+2}

Figure 2. Two-dimensional schema of surface-negative event over a sulcus. Gloor’s schema shows that scalp potential P1 is negative but of lower voltage due to narrowing of the solid angle of negativity (compared with P1 in Figure 1), while P2 is almost isoelectric due to equivalence of topside cortical ribbon negativity and underside cortical ribbon positivity. A channel comparing electrodes 1 and 2 will record a small negative deflection. (Adapted with permission from Gloor P. Contributions of electroencephalography and electrocorticography to the neurological treatment of the epilepsies. Adv Neurol 1975;8:59–105.)

Ω_{2eff} = \Omega_{-2} - \Omega_{+2} \\ \approx 0
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From the scalp EEG. The “volume conduction” effects in scalp EEG result in expansion of apparent electrical fields at the scalp, compared with the sites of the actual underlying electrical generators (Table 1). These electrical activities are influenced by neuronal activities originating in other neocortical areas, in limbic system structures, and especially in the thalamus (Figure 4). Thus, the scalp EEG is a limited sampling of synchronized electrical activities generated predominantly by neocortical pyramidal neurons of gyral crests, and these electrical activities reflect local synaptic activities but also certain types of distant synaptic activities.

Table 1. Determinants of Amplitude, Duration, Morphology, and Topography of Extracranial EEG Oscillations

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<td>Duration of synchronous postsynaptic potentials</td>
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<td>Number of pyramidal cell apical dendrites with synchronous postsynaptic potentials</td>
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<td>Anatomical location-orientation of cortical pyramidal cell layer</td>
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<td>Distances of electrodes from electrical generators*</td>
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Normal EEG patterns represent synchronized oscillations of large groups of neurons; synchrony of these oscillations is more dependent on intracortical interactions during waking and more dependent on thalamocortical interactions during sleep. In general, pathologic EEG findings may reflect dysfunction originating in the neocortical neurons that generate the signal, or dysfunction originating in distant neurons and “projected” to the neocortical generators, or both. Small lesions that ablate cortex near the dorsolateral skull usually cause reduced amplitude in overlying scalp EEG electrodes or produce no change in scalp EEG recordings. Many of the most prominent non-epileptiform EEG abnormalities, including focal or generalized persistent polymorphic delta activity, require lesions or dysfunctions that originate in subcortical white matter or subcortical gray matter structures in order to produce alteration of the scalp EEG.

Epileptiform EEG abnormalities represent synchronized paroxysmal depolarization shifts (PDSs) in cortical neurons, a cellular phenomenon that was reviewed in part 1 of this series. Any PDSs that occur in the thalamus are not directly accessible to scalp EEG recording, of course. Considerable experimental evidence indicates that, in animal...
models of generalized epilepsies and probably also in human epilepsies, synchronized intrathalamic PDSs “pace” the cortex into massively synchronized PDSs that are recordable on scalp EEG.8,9 The generalized epilepsies feature 2 general EEG patterns: generalized spike-wave discharges (of various types) and generalized paroxysmal fast activity (GPFA).10 Either pattern can occur interictally or during seizures.

A single brief burst of PDSs that are synchronized within 1 cortical region may generate a focal interictal spike on the EEG, and repetitive bursts of synchronized PDSs underlie the partial-onset electrographic seizure.11 On scalp EEG recordings, partial-onset seizures are continuous discharges that evolve in field, frequency, and morphology over the period of the discharge.12 The initial field on the scalp EEG may be focal and subsequently become more diffuse, but sometimes the field is initially diffuse (usually termed a “non-localizing” field, as use of the term “generalized field” would confuse the clinician who receives the report of a generalized field at the onset of a partial seizure) and later evolves to become more focal.11 Often the repetitive waveforms are sharply contoured, but only infrequently consist of continuously repeating spike-wave complexes. Thus, partial-onset seizures (those of focal cerebral origin) present a plethora of morphological manifestations on scalp EEG, while generalized-onset seizures (those in which thalamocortical dysfunction paces cortical discharges) present only generalized spike-wave and GPFA patterns; as a rule, by scalp EEG definition, interictal and ictal states are quite distinct in partial epilepsies and quite similar in generalized epilepsies.

The limited sampling of the scalp EEG is fully evident in its limited ability to detect interictal spikes in many patients with localization-related epilep-

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**Figure 4.** Summary of thalamocortical interactions relevant to electroencephalography (EEG) generation. Inhibitory (GABAergic) thalamic reticular (RE) neurons can act to synchronize larger pyramidal neurons (PY) of the specific and nonspecific thalamic nuclei. These larger thalamocortical relay (TC) neurons project excitatorily (with glutamate) and reciprocally to cortical neurons. A single TC neuron typically projects to hundreds or thousands of cortical neurons that occupy a small area, or “cortical column.” Intracortical connections permit cortical columns to influence each other’s synaptic activities. Thus, thalamic RE neurons can synchronize many thalamocortical TC neurons, which in turn can synchronize a larger population of cortical neurons (even enough to coordinate their postsynaptic potentials [PSPs] into oscillations that are detectable with scalp EEG). In slow-wave sleep, the thalamic slow-wave and spindle pacing causes massive cortical neuronal populations to oscillate slowly in synchronized PSPs. In waking and REM states, the thalamocortical pacing is reduced, and smaller synchronized cortical neuronal populations produce lower-amplitude, faster oscillations. IN = interneurons; Pre = prethalamic afferent connections. ( Adapted with permission from Destexhe A, Sejnowski TJ. Interactions between membrane conductances underlying thalamocortical slow-wave oscillations. Physiol Rev 2003;83:1401–53.)
Intracranial electrodes routinely detect spike foci that were never evidenced on the extracranial EEG. In patients with hippocampal-onset complex partial seizures as determined with intracerebral and subdural electrode monitoring, hippocampal spikes (recorded with depth electrodes) typically are not synchronous with ipsilateral temporal lobe spikes that are recorded with sphenoidal and scalp electrodes. Spikes whose extracranial amplitude is maximal at a sphenoidal electrode probably are generated only in basal temporal neocortex. Spikes whose extracranial amplitude is maximal at temporal scalp electrodes probably are generated only in lateral temporal neocortex. These correlates of extracranial EEG spikes were determined with simultaneous subdural and extracranial electrode recordings and with simultaneous magnetoencephalographic and extracranial EEG recordings.

Extracranial EEG recordings of a seizure beginning in a small cerebral region will show ictal discharges only after the ictal discharges have spread to a larger volume of cortex that includes superficial sites. In fact, temporal lobe seizures often show generalized or widespread bilateral distributions of the earliest scalp-EEG–detected changes; in these cases, simultaneous intracranial recordings detect ictal discharges that initially are much more focal and begin earlier than the scalp EEG ictal changes. It is well recognized that deep or highly focal electrographic seizures often are not recorded with extracranial electrodes, unless there is propagation of ictal discharges to sites and volumes of cortex that permit scalp EEG detection. Highly focal seizures that are not detected with scalp electrodes often represent simple partial seizures. During pure amnestic seizures, bilateral hippocampal ictal discharges do not propagate out of the mesial temporal regions and no ictal discharges are detectable with scalp electrodes; pure amnestic seizures are not accompanied by unresponsiveness or other behavioral changes. In patients with no evidence of static encephalopathy or severe unilateral hemispheric dysfunction, it is reasonable to presume that electrographic seizure activity would necessarily involve relatively large bilateral hemispheric volumes of cortex in order to produce complete unresponsiveness and global amnesia during a complex partial seizure, and that such widespread discharges would be detectable with adequately recorded scalp EEG. This tenet is the basis of diagnosis of epileptic and nonepileptic seizures by video-EEG monitoring.

False localization of the earliest ictal discharges on extracranial EEG is a further consequence of the inability of extracranial EEG to record ictal discharges in deep structures and highly focal ictal discharges. When the earliest ictal discharges occur over a focal temporal region on scalp or scalp-sphenoidal EEG, the most common correlate on intracerebral EEG would be initial ictal discharges in 1 hippocampus, followed by propagation to the ipsilateral temporal neocortex (at which time scalp-sphenoidal EEG shows its earliest ictal recording). A less common situation is that of falsely lateralized temporal lobe initial ictal discharges on extracranial EEG; in this situation, intracerebral EEG would record initial ictal discharges in 1 hippocampus, followed by atypical intracranial propagation patterns such that the contralateral temporal neocortex becomes involved in electrographic seizure activity before the temporal neocortex that is ipsilateral to that hippocampus, with the result that the scalp EEG records earliest ictal changes over the contralateral temporal lobe. In some complex cases, scalp-sphenoidal EEG recordings show bilateral independent ictal onsets over both temporal lobes, but intracerebral recordings show that in fact all of the seizures arise in one hippo-
campus, with typical propagation patterns during some seizures and atypical propagation patterns during other seizures.\textsuperscript{21} When the cortex interictally generates a pathological spike-wave complex with a surface-negative spike maximum at the F7-T3 electrodes (which are the “F7-T7” electrodes in the newer nomenclature), the electroencephalographer cannot be certain as to whether the 6 cm\textsuperscript{2} (or larger) spike generator surface was located on the left inferior frontal gyrus, on the left superior temporal gyrus, or on some other nearby surface, but can be reasonably certain that the generator was not located in the left hippocampus, in the left thalamus, or in the right hemisphere. Similarly, when an individual has interictal spikes recorded independently with maxima at the left anterolateral temporal electrodes and at the right anterolateral temporal electrodes, the electroencephalographer cannot determine from these data alone whether the patient has refractory seizures and whether the patient has seizures that arise only in 1 temporal lobe or arise independently in both temporal lobes (or elsewhere).

The true percentage of patients with epilepsy who never have interictal spikes on scalp EEG is not known, due to uncertainties in the true incidence and prevalence of epilepsy by type; variability in EEG techniques (in particular, durations of EEG recordings used by various qualified electroencephalographers); and limitations of scalp EEG in recording spikes from small and deep-seated sites in focal spikes, such that low-amplitude spikes on scalp EEG likely do not constitute definite scalp EEG spikes. Clearly, some syndromes are more likely to present with interictal spikes than are others. For example, mesial frontal lobe epilepsy is among the syndromes least likely to demonstrate interictal spikes despite very prolonged EEG recording.\textsuperscript{156} Conversely, some types of pathological spikes are less likely to be associated with clinical epilepsy than are others. For example, frontal spikes are less likely to be associated with clinical epilepsy than are temporal spikes.\textsuperscript{22}

The “inverse problem” requires a single correct solution to the question of precisely what area of the brain generated electrical dipoles that generated the surface-negative spike or other phenomenon of interest in the scalp EEG recording. Extracranial EEG data cannot be used alone to fully solve the “inverse problem”; the expert electroencephalographer, however, is able to exclude a large range of impossible or unlikely solutions to the inverse problem, and to analyze a delimited set of reasonable possible solutions to the inverse problem; these possible solutions can be compared with nonelectrophysiologic data.

**TECHNOLOGY AND APPLICATIONS OF EEG**

**PRINCIPLES OF HUMAN ELECTROPHYSIOLOGICAL RECORDING**

**Extracranially Recorded EEG**

Standard extracranial electrodes for clinical EEG and video-EEG are scalp electrodes placed in the 10-20 system or the 10-10 system (Figure 5), with additional electrodes for reference or comparison, including cutaneous electrocardiographic electrodes. “Special” extracranial electrodes include scalp electrodes that are placed at particular sites outside of the 10-20 and 10-10 systems with the intention of better recording from a target structure, such as the “true” anterior temporal electrode,\textsuperscript{23} as well as specially designed electrodes placed off the scalp. Nasopharyngeal electrodes were once thought to record well from mesiobasal temporal generators, but they are rather uncomfortable, unstable in positioning, and associated with higher levels of artifactual recordings than are scalp
Sphenoidal electrodes are mildly invasive as they are placed into the masseter muscle under the temporal bone, but are well tolerated chronically (following recovery from acute insertional discomforts) and relatively stable in positioning; recent studies cast doubt on the posited incremental access to mesiobasal temporal generators, however. Foramen ovale electrodes now are rarely used, as the burden of insertional pain and hemorrhagic-infectious risks of foraminal entry appear equal to those of intracranial electrode placement, while selectivity of cerebral sampling with intracranial electrodes far exceeds the sampling offered by foramen ovale electrodes.

Intracranially Recorded EEG (Macro- and Micro-electrodes)

Intracranial electrodes are placed in epidural, subdural, and intra-axial locations with a wide range of electrode morphology (Figure 6). Least invasive are epidural peg or screw electrodes, which are placed through small twist drill holes or burr holes in the skull. Recordings with epidural and all other types of intracranial electrodes markedly reduce myogenic, kinesigenic, and other artifacts compared with extracranial recordings, markedly increase access to electrocerebral oscillations above 50 Hz, and reduce voltage decline related to distance from electrocerebral generators. Penetration of the dura increases rates of hemorrhage and probably of infection but increases access to specific targets. Insertion of subdural electrode strips though burr holes is in theory safer than stereotaxic insertion of intracerebral ("depth") electrodes, as only the latter are expected to penetrate brain substance. Empirical investigations suggest that the course of manual insertion of subdural strips is not always well controlled, however, and unexpected tearing of small bridging veins can cause subdural hemorrhage, while chronic meningeal cicatrix formation and anatomical complexities have caused subdural strips to actually enter the brain substance. Depth electrodes have a more readily controlled course of stereotaxic insertion, and modern imaging permits avoidance of all but the smallest of intra-axial vessels. Direct comparison of depth electrode and subdural strip electrode recordings showed that only depth electrodes record from hippocampal electrical generators and that subdural recording from the parahippocampal region rarely may miss critical ictal onset data. Large subdural electrode grid arrays require craniotomy, which is only
practical to perform unilaterally but which offers superior sampling from cortical surfaces and the opportunity to map cerebral function with direct cortical electrical stimulation (DCES) techniques. It must be borne in mind that subdural grids sample from gyral crests and not from sulcal depressions;
this may be a minor limitation with regard to mapping ictal onset zones, given that local propagation of seizure activity occurs rather consistently, such that gyral crest will be involved early in subjacent ictal onsets, but may be a major limitation in electrostimulation mapping of cerebral function as the current applied to gyral crests is unlikely to map functions at subjacent sulcal fundi.

All types of intracranial electrodes are much more limited in spatial sampling than are scalp electrodes, which benefits the anatomical specificity of ictal recordings and functional maps but which reduces the opportunity to sample a wide cerebral area. If intracranial electrodes are not situated at the actual site of earliest ictal discharges, then the electrodes that are nearest the actual ictal onset zone will appear to be the sites of ictal onset. Effects of inadequate cerebral sampling on localization of the ictal onset zone for resective therapy can be profound and may lead to inefficacious resection with iatrogenic injury to essential cerebral structures. For example, when intracranial electrodes have only been placed in bilateral temporal lobe structures, seizures that originate in frontal lobe limbic system structures such as the insula and orbitofrontal cortex are likely to propagate rapidly into mesial temporal structures (and possibly to propagate so rapidly as to prevent informative parallel analysis of ictal symptoms and signs), in which case the electroencephalographer may naively assume that a temporal lobe contained the ictal onset zone (which should be resected). It would be unsafe to routinely place subdural and depth electrodes into several hundred cerebral sites bilaterally. It therefore is necessary to carefully construct hypotheses concerning the most likely ictal onset zones in the individual patient, in order to select a reasonable number of high-probability intracranial sites for seizure recording, in some cases supplemented by a few “sentinel” electrodes at lower-probability sites (to allow for unexpected but important rejection of the principal hypotheses based on actual seizure recordings). The use of structural and functional imaging data together with extracranial EEG and other data will be discussed in detail in Part 5 of this series.

High-frequency oscillations (HFOs), termed “ripples” (100-250 Hz) and “fast ripples” (250–500+ Hz), are recorded with intracranial electrodes. The burgeoning area of HFO research is being pursued with animal models and human investigations using macroelectrodes (“clinically-sized” contacts with recording surfaces of 1–100 mm²) and smaller microelectrodes. Microelectrode recordings of single neurons and small neuronal assemblies are performed as research studies in human volunteers and are not widely accepted for any clinical indications.

**Magnetoencephalography**

Magnetoencephalography (MEG) has been used in numerous human epilepsy research studies, and in particular to map interictal spike topography and to map functional activated cortical areas. Electrocerebral activities generate magnetic fluxes that are readily detectable with MEG instruments. Unlike EEG signals, at extracranial locations these MEG signals have not been significantly attenuated by distance effects and by effects of intervening tissues. Several epilepsy surgery programs use MEG to detect and localize interictal spikes that are undetectable with scalp EEG, in part to assist in selection of sites for intracranial electrode recording of seizures.

The principal disadvantages of MEG as a potential clinical technique appear to be the considerable expense of MEG instruments (compared with EEG equipment), the demanding expertise
requirements and numerous assumptions necessary to delimit the anatomical range of possible flux sources into a single most likely magnetic generator, and the inability to routinely record spontaneously occurring seizures when seizures are occurring many hours apart. Possibly due to the latter limitation, MEG has not been widely adopted and many MEG experts use MEG primarily for their clinical research and as an adjunctive technique in their clinical practices.

**Signal Averaging**

Evoked potentials (EPs) and other EEG-averaging techniques have considerably extended the clinical applications of EEG in intraoperative monitoring and other applications. Most of these applications are not routine components of epilepsy care. An exception is the use of somatosensory EPs for electrocorticographic mapping of essential motor and sensory cortex in order to avoid iatrogenic injury during resection of frontal lobe and parietal lobe sites of ictal onset. Epileptologists who have not completed comprehensive clinical neurophysiology training should be aware of the considerable complexity of acquiring EPs with extracranial or intracranial electrodes, including the numerous sources of artifacts that afflict EP analysis both in and out of the operating room. The physiology and technology of EPs are complex topics that exceed the purview of this epilepsy-oriented review of clinical neurophysiology.

**Automated Spike and Seizure Detection and Other Automated Analyses**

The clinical utility of automated spike and seizure detection is widely recognized. Early research with computerized event detection algorithms was pursued in multiple laboratories. Currently, the techniques of Jean Gotman and his collaborators underlie essentially all of the detection algorithms that are available with software packages of EEG and video-EEG equipment, often with modifications by in-house engineers of the particular equipment vendor. Most epilepsy-EEG experts use such FDA-regulated spike and seizure detection software to locate epochs of interest among the thousands of minutes of EEG data that are recorded for a single patient during video-EEG monitoring, followed by qualitative analysis to exclude detection of artifacts and to determine the field, frequency, and morphology of spikes and seizures. Mechanical and especially biological sources of artifacts continue to pose major problems for automated analyses of extracranial EEG data in clinical applications.

Other forms of automated EEG signal processing have produced useful insights into seizures, epilepsy, and the EEG signal itself. For example, the initially laborious and complex recording of EEG signals during functional magnetic resonance imaging (fMRI) revealed that focal interictal spikes both activate and deactivate local cortical processing as indirectly measured by fMRI. Available devices and software have rendered fMRI-EEG practical for smaller research teams with less dedicated “magnet time” and fewer research hours, but this technique is not yet an established clinical technique. The research applications of automated EEG signal processing are extensive and beyond the scope of this clinically oriented review.

**PRINCIPLES OF VIDEO-EEG MONITORING**

The impact of routinely available video-EEG has profoundly extended the care of individual seizure patients, not only for those who have epilepsy but especially for those who do not have epilepsy (or have a mixture of both epileptic and nonepileptic seizures). Improved video-EEG techniques also have directly improved planning of
epilepsy surgery, with more efficient, more comfortable, and more widely available recording of multiple seizures in the individual patient. Other indications for video-EEG monitoring (Table 2) include therapeutic monitoring of medication response in nonconvulsive status epilepticus and acute repetitive seizures.

Seizure induction for the purpose of ictal video-EEG recording is primarily achieved with reduction of chronic antiseizure medications and with volitional sleep deprivation. In the past, the rate of seizure recording during presurgical evaluation was increased by inducing seizures with administration of proconvulsant agents such as pentylenetetrazol and with electrical stimulation of intracranial electrodes. These practices were rapidly abandoned after Wieser et al’s landmark study comparing the localizations of “spontaneous” seizures with those of chemically and electrically induced seizures in the same patients showed that many seizures induced chemically and electrically had ictal onset zones that never occurred with the patient’s spontaneous seizures. In some instances psychogenic events have been induced with intense suggestion by hypnosis or similar techniques, but it generally is not clear whether these seizures would have occurred as the individual’s habitual seizure type or whether a highly suggestible individual (who may or may not have epilepsy) has had an atypical event induced with hypnosis. Most epilepsy-EEG experts rely on seizure diagnosis with events recorded with, or without, reduction of antiseizure medications and sleep deprivation.

Paroxysmal behavioral events that involve transient unconsciousness or globally impaired consciousness can be caused by epileptic seizures, by certain types of nonepileptic organic events such as parasomnias and syncope, and by psychogenic nonepileptic events. Many individuals who are transiently unconscious due to a complex partial seizure are unable to recognize and report that they were unconscious, however. In the absence of any means to directly determine whether an individual is conscious, neurologists and others instead assess behavioral correlates of consciousness. In an individual who usually is responsive to voice and touch and who usually is able to later recall verbal and nonverbal stimuli that were presented during a waking state, the paroxysmal and brief occurrence of complete unresponsiveness to voice and touch coupled with later (on regaining normally responsive alert behavior) inability to recall verbal and nonverbal stimuli that were presented during the period of unresponsiveness is a reasonable behavioral definition of unconsciousness.

Considerable harm can result from incorrectly diagnosing psychogenic nonepileptic seizures (“pseudoseizures”), and from diagnosing only psychogenic nonepileptic seizures in an individual who has both epileptic and nonepileptic seizures habitually. For many reasons, most epilepsy-EEG experts definitively diagnose nonepileptic seizures only when the reportedly habitual event has been recorded with technically adequate video-EEG, which permits the expert to examine both the recorded behavior as well as the associated EEG activities during the event. Normal interictal EEGs
are quite common in many forms of epilepsy; a normal interictal EEG in a psychologically distressed patient is not diagnostic of psychogenic seizures. Unchanged scalp EEG activities are common during simple partial seizures; the absence of scalp EEG-recorded ictal discharges is expected during patient-reported seizures in which responsiveness is maintained, although a minority of simple partial seizures do produce scalp-EEG–recorded ictal discharges or nonspecific changes from the baseline EEG. Psychogenic events do not have any pathognomonic age or gender range, semiological history, interictal EEG findings, or imaging findings.45,47 Risk factors for psychogenic events can be found on mental health history and on neuropsychological testing, but none of these risk factors excludes the possibility of epilepsy or organic nonepileptic events. Similarly, recording the habitual behavioral events with video-EEG monitoring (or polysomnography with additional EEG electrodes) is necessary to distinguish parasomnias and REM sleep behavior disorder from nocturnal epileptic seizures, as well as from nocturnal psychogenic events. Although it appears to be true that paroxysmal psychogenic events do not arise directly from sleep states, it is relatively common to encounter individuals who report sleep-onset events that are shown on video-EEG to be psychogenic events arising during a period of nighttime waking state. Patients and their observers often report that a “seizure” occurred during ambulatory EEG recording, but the electroencephalographer will not be able to determine what behaviors actually occurred in the absence of video recording. Recording habitual behavioral events with video-EEG monitoring is generally required for confident diagnosis of psychogenic nonepileptic seizures, and usually is quite helpful in diagnosing epileptic seizures and “organic” nonepileptic seizures such as parasomnias.

The central tenet of diagnostic video-EEG might be stated as: Electrographic seizure activity must involve bilateral cortex of volumes sufficient to be detected with adequately recorded scalp EEG in order to produce complete unresponsiveness and global amnesia in patients with no evidence of static encephalopathy or severe unilateral hemispheric dysfunction. In such patients, ictal discharges in cortical volumes too small to be detected with adequate EEG also cannot globally alter awareness, responsiveness, and memory formation. Thus, in a patient who has normal or nearly normal responsiveness and memory in the absence of seizures, if the patient has behavioral testing during an event with complete unresponsiveness to voice and touch, for which the patient subsequently has no memory, and has technically adequate EEG recording at this time with waking or lightly drowsy EEG activities that are unchanged from baseline, the patient apparently has had a psychogenic event. Epileptic seizures that cause global unresponsiveness and global amnesia, such as complex partial seizures and absence seizures, consistently have ictal discharges on adequately recorded scalp EEG. Organic nonepileptic events that cause global unresponsiveness and global amnesia, such as syncope and parasomnias, have EEG findings other than baseline waking or lightly drowsy findings. Under current understanding of cerebral function, only psychogenic processes would be likely to account for such events. This tenet is logical, concordant with current knowledge of cerebral function, and fits with extensive clinical experience, but cannot be considered to be “proven” in all possible situations of unconsciousness. When video-EEG recording of a habitual event is the principal basis for diagnosis of a psychogenic nonepileptic seizure, adherence to requirements of technical adequacy of EEG recording and of
behavioral testing are likely to be quite important. In many cases, the EEG diagnosis can be supplemented with behavioral analysis of particular motor behaviors during habitual events and other data in order to strengthen the diagnosis.

**PRINCIPLES OF MAPPING OF ELOQUENT CORTEX WITH DIRECT CORTICAL ELECTRICAL STIMULATION**

DCES is usually performed over cortical surfaces for the purpose of mapping motor, sensory, or cognitive functions, but has also been performed with intracerebral electrodes for stimulation of the hippocampus or other deep structures or for the purpose of inducing seizures. In all applications of DCES, patient safety is of paramount importance. Currently available (FDA-approved) stimulators have hard-wired stimulus isolation circuits, and providing that the isolation circuit is checked for integrity by qualified personnel, such a stimulator can be safely used in the electrical environment of any operating room without arranging additional electrical isolation. Additionally, modern stimulators provide current pulses of alternating polarity so that no net DC current is applied to the brain, and also provide stimulation of constant current so that it is not necessary to measure the impedance between particular electrodes at each cortical site in order to calculate the voltage to be passed to achieve the desired current.

Electrocorticography is performed concurrently with DCES in order to recognize afterdischarges and electrographic seizures that will affect the interpretation of any behavioral changes induced by stimulation, as well as for purposes of patient safety. Safety is also assured by limiting the total charge delivered and the charge density over the stimulated volume of tissue. It has been demonstrated in humans that charge densities of less than about 55 microcoulombs/cm²/phase do not induce histologically detectable lesions of subsequently resected tissue. Standard electrode strips and grids have an uninsulated surface area of about 12 to 13 mm² per contact with the cortex; with bipolar wand stimulators, the size of the electrode surface area varies but is often about 4 mm². The larger electrodes have a smaller charge density per phase for the current intensity that is produced by the stimulator. The stimulator should produce trains of current in alternating polarity, so that there is no net charge applied over the duration of each stimulation. Stimulation is typically applied in trains lasting 2 to 5 seconds at a rate of 50 phases/second with each phase lasting 0.3 ms. Stimulation typically begins at low intensities of current; when these stimulation parameters are used with standard subdural strip and grid arrays, this would be 0.5 milliamperes of current. During cortical function mapping, if no afterdischarges or seizures occur and no behavioral effects are noted, current intensity is typically increased sequentially to a maximum of 15 milliamperes, if using standard subdural arrays. The current setting on the stimulator should be adjusted to achieve comparable charge densities for the particular electrode surface area exposed by the particular bipolar wand stimulator.

Afterdischarges are interictal epileptiform activities that may consist of single or rhythmically or irregularly repetitive spike-wave, sharp wave-slow wave, or polyspike-wave discharges; less often, they consist of paroxysmal fast activity that appears relatively monorhythmic. At an individual site of stimulation, the afterdischarges may strongly resemble the spontaneous interictal epileptiform activities noted to occur during the baseline pre-stimulation period of electrocorticography, so that at times it may be difficult to distinguish an afterdischarge from a frequently occurring spontaneous
epileptiform discharge that by chance occurred at the end of cortical stimulation. Continuing stimulation at a site at which afterdischarges have been induced can subsequently induce an electrographic seizure, particularly if current is progressively increased despite the occurrence of afterdischarges; this is undesirable if a secondarily generalized seizure is induced. If the purpose of stimulation is cortical function mapping, postictal regional cerebral depression may confound further behavioral testing. On the other hand, repeated stimulation at the same current (or transiently at a lower current) at a site at which afterdischarges have been obtained can sometimes elevate the threshold for afterdischarge production.51 It may be desirable to elevate afterdischarge thresholds when the purpose of stimulation is language mapping, since relatively higher current densities are required for adequate local language mapping than for motor or sensory mapping over the primary sensorimotor cortices. A prolonged afterdischarge may be difficult to distinguish from an electrographic seizure. When afterdischarges or electrographic seizures occur at a particular site, it cannot be concluded that that site is ordinarily responsible for the induced behavioral responses, since there may have been propagation of the electrical events to distant sites at which recording electrodes have not been placed, and activation or deactivation of the ordinary neuronal activities at these distant sites may be responsible for the observed behavioral change.

INTERICTAL EPILEPTIFORM ACTIVITIES

INTERICTAL EPILEPTIFORM ACTIVITIES ON SCALP EEG

Focal Spikes and Sharp Waves

Temporal and frontotemporal spikes. Temporal spikes and sharp waves are the most commonly encountered of focal epileptiform activities. They are usually seen in disorders of temporal lobe epilepsy, such as mesial temporal sclerosis (MTS). These discharges usually have a maximum over the anterior temporal region and have a surface-negative polarity (in contrast to the Rolandic spike).52 They are more frequent and more prominent during sleep and drowsiness (Figure 7). They may appear as spike followed by slow-wave activities and are often accompanied by background activities such as ipsilateral temporal theta or delta slowing. Temporal lobe spike should be distinguished from small sharp spikes, which is a normal variant during light sleep. Small sharp spikes usually have short duration, low amplitude, a brief aftergoing slow wave, a wide field, and an undisturbed background activity. They are often seen bilaterally. Small sharp spikes are also called benign epileptiform transients of sleep (BETS).53,54 It is widely considered that over 90% of patients whose interictal EEG shows pathological temporal lobe spikes will actually have temporal lobe seizures, although the definitive population study to

Figure 7. Right temporal spike. A single spike can be seen at the right temporal region in an 83-year-old man with a history of intractable seizures.
establish this clinical experience is yet to be published. Clearly, the occurrence of pathological temporal lobe spikes on an interictal EEG would not be expected to prevent psychogenic nonepileptic seizures in an individual who probably has temporal lobe epilepsy; ictal EEG is necessary for definitive diagnosis of events that have been controlled with appropriate medications.55,56

**Centrotemporal spikes.** Rolandoic interictal epileptiform discharges (IEDs) are also called centrotemporal spikes. This abnormality is seen in children with a specific epileptic syndrome, Rolandoic epilepsy, also referred to as benign childhood epilepsy with centrotemporal spikes (BCECTS).57,58 This syndrome is common in childhood, with onset between 2 and 12 years old. It is benign in the majority of cases and seizures usually disappear at age 15 to 18 years. The Rolandoic IEDs can be unilateral or may be seen bilaterally independently. These spikes are usually frequent, sometimes in short runs, especially during sleep or drowsiness, and decrease in frequency with hyperventilation (Figure 8). They usually have a triphasic morphology and occur in a rate of 1.5 to 3 Hz. In most partial epilepsies, a focal spike arises from a radially oriented dipole, with the negative end pointing to the scalp and the positive end pointing to the deep white matter, such that scalp electrodes record only a surface-negative maximum. One unique feature of the Rolandoic IEDs is that a tangential dipole often is seen on the scalp electrodes, with centrotemporal negativity and frontal positivity.59,60

**Frontal and frontocentral spikes.** Frontal and frontocentral spikes are commonly seen in frontal lobe epilepsies, which as a group are the second most common sites of partial epilepsy after temporal lobe epilepsies. The IEDs are not as stereotypically formed or diagnostically specific as those in mesial temporal lobe epilepsy. Frontal interictal epileptiform activities may originate from orbitofrontal cortex, frontal pole, dorsolateral frontal cortex, cingulate gyrus, or insular cortex, as determined using intracranial electrodes. As for hippocampal spikes, many frontal sites that are deep to the skull surface do not generate spikes that are routinely detectable with scalp electrodes. Dorsolateral and frontopolar gyral crests are best situated to generate spikes that are detectable with scalp electrodes. Ictal behavior and ictal EEG may be highly variable and nonspecific in frontal lobe epilepsies. Therefore, frontal lobe epilepsies pose a greater challenge in terms of diagnosis with interictal EEG and with other tools than does mesial temporal lobe epilepsy.61

**Occipital spikes.** Occipital spikes may be seen in patients with occipital structural abnormality or in genetic epilepsy with occipital spikes. Genetic childhood epilepsy with occipital spikes may be seen in 2 subtypes: Panayiotopoulos syndrome and Gastaut syndrome. Panayiotopoulos syndrome usually has an early onset at age 3 to 5 years. The patients usually have nocturnal infe-
quent seizures, with lateralized gaze and ictal vomiting. Prognosis is usually excellent in this subtype. Gastaut syndrome is usually late onset at age 7 to 9 years. Seizures usually involve visual symptoms and postictal vomiting. These patients tend to respond to medications. Gastaut syndrome usually has a less favorable prognosis than the Panayiotopoulos syndrome. The EEG features of these 2 variants are essentially indistinguishable. They have occipital dysphasic spikes or sharp waves with high-voltage negative peak followed by positive peak with a normal background activity.\(^\text{62,63}\)

**Generalized Spikes and Sharp Waves**

**Classic generalized 3-Hz spike-wave discharges.** Three-per-second spike-and-slow-wave in certain clinical settings is virtually pathognomonic for childhood absence epilepsy (pyknolepsy) in children 3 to 15 years old, but generalized 3-Hz spike-wave discharges also occur in juvenile absence epilepsy, some instances of juvenile myoclonic epilepsy, and often in the benign partial epilepsies of childhood.\(^\text{59}\) Thus, in contrast to an epileptiform pattern that is nearly pathognomonic for a single syndrome (such as hypsarrhythmia for West syndrome), generalized 3-Hz spike-wave discharges are a very important component of multiple electroclinical syndromes. The scalp EEG discharges consist of generalized repetitive spike-and-slow-wave complexes at 3 Hz that are symmetric and anteriorly predominant on a normal background.\(^\text{64–66}\) They usually occur frequently and patients typically have brief staring spells that last for less than 30 seconds. Eye blinking, automatisms, and myoclonic jerks are common when the discharges last for more than 3 to 4 seconds. These complexes may not be strictly 3 Hz. The frequency often begins at 3.5 to 4 Hz and gradually slows to 2.5 Hz (Figure 9). Hyperventilation and high-frequency photic stimulation may trigger the 3-Hz spike-and-wave discharges in children with childhood absence epilepsy. The triggered 3-Hz bursts often outlast the duration of photic stimulation itself. Background of the EEG in childhood absence epilepsy is usually normal. However, in a minority of patients, interictal abnormalities may be seen. Occipital intermittent rhythmic discharge activity (OIRDA) can be seen in about one-fifth (15%–38%) of patients with childhood absence epilepsy.\(^\text{67}\) OIRDA is strongly age-related and is rarely seen in individuals older than 15 years. The overall occurrence of 3-Hz spike-and-wave discharges on interictal EEG is highly associated with the extent of absence seizure control, such that EEG can be used to assess seizure control in absence epilepsies.\(^\text{68}\)

**Generalized fast spike-wave and polyspike-wave discharges.** Fast generalized spike-wave and polyspike-wave activities consist of generalized, bisynchronous frontally predominant spike-and-wave activities that begin at 3.5 to 6 Hz and end at 2.5 to 3 Hz.\(^\text{69}\) Polyspikes are commonly
seen in these spike-and-wave complexes and are often prominent at the beginning of these epileptiform activities (Figure 10). The background of this EEG is usually normal. This EEG pattern is commonly seen in genetic epileptic syndromes such as juvenile myoclonic epilepsy (JME) and juvenile absence epilepsy (JAE). Although polyspikes and polyspike-and-slow-wave activities are characteristic of JME and JAE, they are not pathognomonic.70 The association between generalized polyspikes and myoclonus is observed not only in JME, but also in progressive myoclonus epilepsies and various other conditions. Hyperventilation, eye closure, and photic stimulation can activate these epileptiform activities. In a minority of cases, these epileptiform discharges can be elicited only with hyperventilation or photic stimulation.71,72

**Generalized slow spike-wave discharges.** Slow spike-and-wave complexes (formerly called *petit mal variant*) differ from typical 3-Hz spike-and-wave and fast spike-and-wave activities in that (1) they consist of 1.5- to 2.5-Hz generalized spike-and-wave activities, (2) the “spike” component is usually a sharp rather than a spike, and (3) they are usually not triggered by hyperventilation or photic stimulation. The complexes may be symmetrical or bilateral synchronous, or they may be asymmetrical or bilateral asynchronous with shifting asymmetry.73,74 These patterns occur in Lennox-Gastaut syndrome, which is characterized by a triad of mental retardation, intractable epilepsy with multiple seizure types, and slow spike-and-wave activities on EEG (Figure 11). Generalized slow spike-wave discharges also occur in other symptomatic generalized epilepsies.

**Secondary bilateral synchrony.** Generalized interictal epileptiform activities can be truly generalized or produced by a focal epileptogenic focus. The truly generalized interictal epileptiform activities are currently thought to originate in the thalamus, which is referred to as the corticoreticular theory. The seemingly bilaterally synchronous generalized epileptiform activities can also be triggered by an epileptogenic focus, which may trigger a mirror image cortical region by rapid transcallosal transmission or through thalamus. This process is referred to as secondary bilateral synchrony.75 Secondary bilateral synchrony is commonly trig-
Triggered by a mesial frontal focus, which is best detected by transverse bipolar montages (Figure 12). Primary and secondary bilateral synchrony have completely different clinical implications and should be carefully distinguished in clinical practice.

**Atypical generalized spike-wave discharges.** Each stereotypical form of generalized spike-wave discharges has a range of variability, with shifting maxima that usually are on average at the fronto-central midline, and with some variability in the rate and rhythmicity of the spike-wave complexes (whether slow, 3 Hz, or fast). When focal amplitude maxima are highly lateralized, rate and rhythms are excessively variable, and other features exceed the usual degree of stereotypy for one of the major types of generalized spike-wave discharges, the generalized discharges are usually termed **atypical generalized spike-wave discharges**. Some of these atypical generalized spike-wave discharges may represent secondary bilateral synchrony, but many do not. Such atypical generalized spike-wave discharges most often occur in progressive myoclonic epilepsies and other syndromes with major interictal cerebral dysfunction, but they also can occur in idiopathic generalized epilepsies. A predominance of generalized theta slowing (rather than delta slowing) with atypical generalized spike-wave and polyspike-wave discharges in early childhood suggests Dravet syndrome, although clinical history is necessary to make this electroclinical syndromic diagnosis. When the frequency reaches 6 Hz, they must be distinguished from 6-Hz phantom spike-and-wave activities, which are benign variants with more focal, lower-amplitude discharges.

**Continuous spike-and-wave during sleep.** When children have generalized spike-wave discharge during more than 85% of the non-REM sleep recording, continuous spike-and-wave during sleep is diagnosed. Further clinical information will be necessary to distinguish the associated electroclinical syndromes of Landau-Kleffner syndrome versus epileptic encephalopathy with continuous spike-and-wave during sleep.

**Multifocal independent spikes.** Multifocal independent spike discharges (MISD) are defined as having epileptiform waves or spikes in both hemispheres with 3 or more independent foci. The focal maxima of 3 or more spike foci must be at least 2 interelectrode distances apart in the 10-20 system. Patients with MISD often have frequent seizures that are intractable to multiple antiepileptic drugs and multiple seizure types including generalized tonic-clinic seizures. They often have severe cerebral dysfunction and developmental delay. MISD is closely related to hypsarrhythmia and slow spike-and-wave activities. Many patients with hypsarrhythmia have evolution of interictal EEG findings...
from hypsarrhythmia into MISD, then eventually into a predominance of generalized slow spike-and-wave complexes.

**Other Interictal Epileptiform Activities on Scalp EEG**

**Temporal intermittent rhythmic delta activities.** Intermittent rhythmic delta activities are patterns of brief bursts of sinusoidal or saw-toothed waveforms that often occur for 2 to 6 seconds. They are most commonly observed in the frontal region bilaterally synchronous and are termed FIRDA. When the focus is the temporal region (TIRDA), they are usually unilateral (Figure 13). TIRDA is highly indicative of epileptogenic potential and is closely related to MTS and mesial temporal lobe epilepsy. TIRDA is generally considered to have the same clinical significance as temporal lobe interictal epileptiform discharges.

**Periodic lateralized epileptiform discharges and bilateral independent periodic lateralized epileptiform discharges.** Periodic lateralized epileptiform discharges (PLEDs) are epileptiform discharges that occur at regular intervals, usually every 0.5 to 4 seconds, and have a single unilateral spike maximum. They are classically triphasic with a spike followed by a slow wave, typically with generalized irregular delta-theta slowing and predominance of slowing over the PLED hemisphere. In some cases both hemispheres generate PLEDs independently as bilateral independent periodic lateralized epileptiform discharges (BiPLEDs). PLEDs usually indicate a focal pathology and are most commonly the result of cortical stroke, tumors, or herpes simplex virus encephalitis (Figure 14). The PLEDs pattern may last for days or even weeks. Seizures occur in almost 80% of patients with PLEDs. In his classic study of PLEDs, Chatrion emphasized that the PLEDs pattern is highly associated with acute encephalopathy (electrographically manifested as generalized slowing) and with a focal structural lesion (electrographically manifested as repetitive lateralized spiking). While PLEDs in themselves do not typically evolve in field frequency and morphology to the same extent as do partial seizures on scalp EEG, in some cases additional low-amplitude faster (or less often, slower) frequency activities consistently occur in the interval between each lateralized spike-wave complex.

**Figure 13.** Temporal intermittent rhythmic delta activities (TIRDA). A burst of left temporal delta activities in a 33-year-old man with history of temporal lobe epilepsy.

**Figure 14.** Periodic lateralized epileptiform discharges (PLEDs). Occipital periodic epileptiform activities in a 55-year-old man with a history of stroke and seizures.
of the PLEDs; this phenomenon has been termed “PLEDs-plus.” The currently prevailing opinion is that PLEDs sometimes represent the scalp EEG manifestation of deep-seated seizures, but usually are an interictal phenomenon. The PLEDs-plus and BiPLEDs patterns appear more likely to be associated with ongoing seizures than are unilateral “simple” PLEDs. Although occurrence of PLEDs usually is monophasic and nonrecurrent, in some cases PLEDs can later recur in patients whose lesion is static (such as a chronic cerebral infarction) but who have a major acute encephalopathic insult (such as ethanol withdrawal) well after the acute phase of the focal lesion.

**Generalized periodic epileptiform discharges.** Generalized periodic epileptiform discharges (GPEDs) are also called bilateral periodic epileptiform discharges (BiPEDs). They consist of generalized epileptiform discharges that are symmetric and synchronous. They tend to be anterior predominant. The amplitudes of the spikes are usually 100 to 1000 µV (Figure 15). GPEDs are the result of a variety of pathological conditions that are likely to produce structural abnormalities, such as anoxic injury, subacute sclerosing panencephalitis, and Creutzfeldt-Jakob disease. GPEDs can occur as an interictal pattern, as generalized spike-wave complexes recurring every 0.5 to 4 seconds monorhythmically or irregularly, superimposed on a generalized delta-theta background, in various severe encephalopathies, or with additional features of evaluation or cycling in nonconvulsive status epilepticus (see further below). BiPEDs (GPEDs) must be distinguished from BiPLEDs, as the former are bilaterally synchronous and the latter are bilateral independent, asynchronous, periodic epileptiform discharges.

**Generalized paroxysmal fast activity.** GPFA is a burst of beta activities that is commonly in the range of 10 to 25 Hz, with a generalized and usually symmetrically frontocentral predominance. (Focal or hemispheric paroxysmal fast activity occurs infrequently and does not have the same clinical associations as GPFA.) GPFA typically has sudden onset and resolution, and the amplitude is occasionally decreased compared to the background slow-wave activities (Figure 16). When GPFA amplitude is severely decreased, the beta activities may not be immediately evident and the GPFA may appear to represent a generalized attenuation such as might occur due to arousal; the pathological generalized beta activities will be evident when the display gain is increased, however. In addition to occurring in brief bursts interictally and usually in sleep, longer runs of GPFA typically occur in tonic seizures and mental retardation.

**Hypsarrhythmia.** Hypsarrhythmia is a rather unique EEG pattern with chaotic, disorganized, asynchronous, very high-voltage (often >300 mV) diffuse slow waves intermixed with multifocal spikes and slow waves (Figure 17). This pattern occurs in West syndrome in young children,
which consists of a triad of infantile spasm, psychomotor development delay, and EEG pattern with hypsarrhythmia. The onset of West syndrome is mostly in the first year of life. The pattern of hypsarrhythmia is usually only seen in the early stage of the infantile spasm, and the EEG may evolve into less chaotic, lower-amplitude, slow spike-and-wave activities. The atypical forms of modified hypsarrhythmia include asymmetric hypsarrhythmia, hypsarrhythmia with a consistent focus of abnormal discharge, hypsarrhythmia with episodic attenuation, hypsarrhythmia with primarily high-voltage slow activity and paucity of sharp-wave or spike activity, and hypsarrhythmia with increased interhemispheric synchronization. Among these modified hypsarrhythmias, asymmetric hypsarrhythmia is most commonly encountered.92

**Burst-suppression.** Interictal EEGs in the neonatal period show burst-suppression patterns in the Ohtahara syndrome and early-myoclonic encephalopathy.93,94 Burst-suppression is not specific to other epileptic syndromes, although it may be encountered during aggressive medication therapy of status epilepticus or status-associated anoxia.

**Photoconvulsive responses.** Photoconvulsive responses, also called photoparoxysmal responses or photoepileptiform responses, are generalized spike-wave discharges activated by repetitive photic stimulation. Red light is most effective in eliciting photoconvulsive responses.95 These responses are most often induced at photic frequencies of 10 to 20 Hz. The EEG pattern may be anterior or occipital predominant, generalized, bisynchronous, or strongly lateralized. Photoconvulsive responses are associated with different types of generalized seizures such as generalized tonic-clonic seizures, myoclonic seizures, or absence seizures. Most of the observed photoconvulsive responses are poorly formed spike-and-wave or polyspike-and-wave complexes.96,97 Photoconvulsive responses must be distinguished from photomyogenic responses that are nocerebral, nonepileptiform in nature. Photomyogenic responses are caused by subtle eye movement and frontotemporalis myogenic artifacts (Figure 18). They are time-locked with the photic stimulations and disappear when the light
flashes discontinue, whereas the photoconvulsive responses will usually outlast the photic stimulation for a few seconds.98

INTERICTAL EPILEPTIFORM ACTIVITIES ON INTRACRANIALY RECORDED EEG

Intracranial EEG recording may obtain critical information when scalp EEG recording and other evaluations do not definitively localize the ictal onset zone. Intracranial EEG is mainly used for epilepsy surgery presurgical evaluation and cortical functional brain mapping. Two types of intracranial monitoring techniques are commonly used: depth electrode and subdural electrode recording.99 The intracranial EEG recording is reviewed with the same principles as the scalp EEG with a few differences. Intracranial signals usually have few artifacts because the electrodes are in a relatively fixed position relative to the cortex and have no muscle contact. Although potentials recorded with intracranial electrodes can be displayed in bipolar or referential montages, they are usually grouped by lobar location, such as anterior or posterior temporal lobe. The fast frequencies are not filtered by the scalp and skull, which makes some of the normal variants quite spiky, such as wicket spikes, alpha rhythm, beta activities, mu rhythm, and so forth. Interictal epileptiform activities may also look different in the intracranial recording as compared to the scalp recording. They usually have shorter duration and much higher amplitude (4- to 5-fold higher) (Figure 19). Therefore, data from the intracranial recording must be interpreted with caution. While the intent of intracranial recording is mapping of ictal onset zones, some information may be gained with examination of the interictal spikes.100

ICTAL EPILEPTIFORM ACTIVITIES AND VIDEO-EEG MONITORING

SCALP EEG AND VIDEO-EEG IN EPILEPSY

Partial Seizures

Ictal EEG recording is a crucial step in the presurgical evaluation for epilepsy surgery in patients
with partial epilepsy. Partial-onset ictal EEG discharges consistently evolve in field, frequency, and morphology, whether or not a focal maximum is evident at the onset of the discharge. Typical ictal rhythms include background attenuation of the initial EEG change, start-stop-restart phenomenon, irregular 2- to 5-Hz lateralized activity, 5- to 10-Hz sinusoidal wave, low-amplitude fast activities, or repetitive epileptiform discharges. The reasons for the diversity of the EEG manifestations are likely multifactorial, which may include location of the onset (mesial versus lateral), underlying pathology, state of the patient during recording (wake versus sleep), antiepileptic medication use, and route of seizure propagation.101,102

With scalp EEG recording, simple partial seizures do not have a clear electrographic correlation in 60% to 90% of cases.103 On the other hand, essentially all complex partial seizures have EEG changes with technically adequate scalp EEG recording (Figure 20). Habitual automatisms in some patients generate artifacts that consistently obscure scalp EEG discharges, however. In patients with epileptic auras (simple partial seizures with subjective manifestations) preceding complex partial seizures, an aura typically precedes any ictal discharge on scalp EEG by many seconds, due to the usually deep and focal localization of the aura generator. In patients who have complex partial seizures without a preceding aura, it is common to observe ictal discharges before there are definite automatisms; altered consciousness frequently precedes automatisms, but an initial motionless stare may not be evident on video analysis unless the patient happens to be conversing at the onset of the seizure. Temporal lobe epilepsy is the most common syndrome that is evaluated for epilepsy surgery. The interictal, ictal, and postictal EEG recordings usually demonstrate characteristic findings in temporal lobe seizures. High-amplitude, rhythmic, sharply contoured theta

Figure 20. Right temporal lobe partial seizure. The first page started with the chewing artifact, followed by right temporal region rhythmic activities which evolved in frequency and amplitude over time.
activities of 5 Hz or faster are a hallmark of complex partial seizures in mesial temporal lobe epilepsy. This pattern usually occurs only during a portion of the electrographic seizure, and it may be preceded by focal temporal-maximum discharges of other frequencies and morphologies that evolve into the focal theta discharges, or by nonlocalized rhythmic discharges that later evolve into the focal theta discharges.12 Up to 80% of patients who have complex partial seizures of mesial temporal onset will have this focal theta pattern during some or most of their complex partial seizures. Importantly, this focal temporal-maximum theta pattern on scalp EEG also can occur with seizures which begin in the limbic system outside of the mesial temporal structures (such as the insula) or in ipsilateral temporal lobe neocortex as shown by concurrent intracranial recording, when the ictal discharges propagate into mesial temporal structures during the complex partial phase of the seizure.21 Figure 20 shows the onset and evolution of a right temporal lobe onset seizure, which has mild attenuation of the background activities at the onset and evolves to 6- to 7-Hz sinusoidal activities. Frontal lobe seizures are also commonly encountered in epilepsy surgical evaluation. However, frontal lobe seizures often do not have a clear EEG correlate due to artifacts in complex partial seizures, making this a significant challenge for clinicians in presurgical evaluation.104 Occipital- and parietal-onset seizures are less common than temporal lobe seizures, and may be simple partial seizures, complex partial, or secondarily generalized seizures, usually with clear localization on scalp EEG for diagnosis, although intracranial recordings are necessary for surgical planning.105 They may begin with visual phenomenon and progress into a generalized tonic-clonic seizure. Headaches may occur during or after the seizures.106 Overall there is a greater tendency for seizures of mesial frontal and mesial occipital origin to be falsely lateralized on scalp EEG, as compared with intracranial recordings in the same individuals whose seizures were previously or simultaneously recorded with scalp EEG.107

Generalized Seizures

Generalized seizures involve both cerebral hemispheres, with ictal discharges of various forms of generalized spike-wave or GPFA patterns from onset when the EEG is not obscured by artifacts. Generalized seizures can be divided into generalized tonic-clonic, tonic, atonic, clonic, myoclonic, and absence seizures. Generalized seizures usually are associated with EEG changes with scalp EEG recording. In particular, generalized tonic-clonic seizures are almost always associated with EEG changes; although the ictal onset and ictal discharges can be entirely obscured by myogenic-kinesigenic artifacts, the postictal depression is nearly always evident as postictal generalized attenuation followed by increasing amplitudes of generalized slowing with gradual return to the interictal baseline. Significant myogenic artifact usually makes them difficult to interpret. In a secondarily generalized seizure, a focal onset often is seen at the beginning of the seizure, if the background is not obscured by artifacts. However, the focal onset may not be obvious if there is rapid spread (rapid secondary bilateral synchrony).82,108 Simple staring spells can be seen with absence seizures, but also with complex partial seizures and psychogenic events, so video analysis requires simultaneous EEG analysis. On the other hand, the ictal behaviors of a generalized tonic-clonic seizure are generally so distinct from those of a psychogenic convulsion that the video analysis in itself provides considerable diagnostic significance.
Nonconvulsive Status Epilepticus and Other Status Epilepticus

Nonconvulsive status epilepticus (NCSE) is an important entity for clinicians to recognize. Recording EEG is necessary to confirm a diagnosis of suspected NCSE, and in some cases a “bland,” nonfluctuating encephalopathy is surprisingly found to be caused by NCSE. Altered behaviors during NCSE can be confused with other conditions such as episodic behaviors of dementia. The ictal discharges in NCSE may be lateralized, as often is observed in complex partial status epilepticus, or may consist of periods of GPEDs that persist or alternate with generalized slowing or less clearly epileptiform alternating patterns. “Spike-wave stupor” is an electroclinical observation in a continuously encephalopathic patient that can arise from uncontrolled complex partial status epilepticus (in partial epilepsies), from absence or atypical absence status epilepticus (in generalized epilepsies), and probably also “de novo” (in a patient who was not previously known to have epilepsy). It is often difficult to distinguish between GPEDs that occur during or after status epilepticus from those due to other causes such as severe encephalopathy or diffuse cerebral injury. Continuous video-EEG monitoring usually is quite useful in evaluating therapeutic response in NCSE, and also in patients with acute repetitive seizures who are not in full-blown NCSE.

Recording of EEG is not necessary to support the clinical diagnosis of generalized convulsive status (GCSE), and waiting for EEG can compromise patient care. The diagnosis of GCSE is almost always made by observation of the patient. Rarely, the patient arrives comatose late in the course of untreated GCSE, when muscle activation during cerebral discharges has markedly diminished. The epileptologist should be aware of the typical evaluation of EEG findings in uncontrolled GCSE. Detailed observations of non-human GCSE demonstrated a progressive sequence of EEG alterations in untreated GCSE: (1) discrete seizures; (2) merging seizures with waxing and waning amplitude and frequency of EEG rhythms; (3) continuous ictal activity; (4) continuous ictal activity punctuated by low-voltage “flat periods”; and (5) periodic epileptiform discharges on a “flat” background. For a patient who arrives at the emergency department comatose, an EEG recording that shows the fourth or fifth of these patterns might be suspected for late GCSE, given that the motor convulsions may be rather subtle late in GCSE. Continuous EEG monitoring can be useful in evaluating therapeutic response in such conditions.

SCALP EEG AND VIDEO-EEG IN NONEPILEPTIC CONDITIONS

Syncope

Syncope may be seen in patients of all ages. The cause of syncope is diverse, including vasovagal, reflex, and orthostatic hypotension. Recurrent syncope may mimic seizures in that patients may have a brief period of tonic-clonic movement of their limbs and body or they may have incontinence during the episode. The electrocardiogram tilt-table test is an effective tool for diagnosis in most of these cases, but when recurring events feature unusual behaviors, combined tilt-table testing and video-EEG monitoring may better elucidate the nature of the events. During a purely hypotensive syncopal event, the EEG will demonstrate increasing generalized slowing which may progress to a brief isoelectric period if hypotension is not rapidly reversed, followed by rapid resumption of baseline EEG activities on cerebral reperfusion (Figure 21).
Parasomnias

Parasomnias are part of sleep disorders that manifest as abnormal nocturnal behavioral events. The differential diagnosis of unusual nocturnal behaviors includes night terror, nightmares, bruxism, somnambulism, confusional arousal, and REM sleep behavior disorder. Frequently, these behavioral events may be confused with epileptic seizures, especially those of frontal lobe origin. Video-EEG monitoring or polysomnography can be quite effective in clarifying the diagnosis. Video-EEG monitoring often demonstrates normal awake or drowsy patterns when the target events are not occurring and state-appropriate EEG activities during the target events in parasomnias. Slow-wave sleep patterns are observed during somnambulism and other parasomnias, but normal REM patterns occur during events of REM behavior disorder. Analysis of video-recorded behaviors is essential and is provided by either video-EEG or polysomnography. Limited numbers of scalp EEG electrodes are provided with standard polysomnography, such that epileptic discharges over the temporal lobes could be missed; modern sleep laboratory equipment offers extra channels for a full array of 10-20 system electrodes, which must be used when the intent is to record unusual nocturnal behaviors. No epileptiform activities or electrographic seizures are seen during sleep disorder events. The epilepsy-electrophysiology expert should be familiar with the range of motor behaviors that can occur during disordered sleep.

Other Organic Nonepileptic Events

Organic encephalopathy or organic brain diseases from a variety of causes may produce confusion or altered level of consciousness. The differential diagnosis includes toxic and metabolic encephalopathy, infectious processes, Alzheimer’s disease, Creutzfeldt-Jakob disease, and delirium. These conditions may also produce epileptic seizures and postictal states. Video-EEG monitoring or routine EEG may be used to make a definitive diagnosis. The EEG usually shows generalized slowing of the background activities. The degree of EEG abnormalities usually parallels the severity of the condition.

Psychogenic Nonepileptic Events

Psychogenic non-epileptic seizures (PNESs), also called “pseudoseizures,” account for up to 10% of clinically diagnosed epilepsy cases and
perhaps 20% to 30% of intractable cases. Furthermore, PNES can coexist with epileptic seizures in the same individual, and PNES can even develop after epileptic seizures are effectively controlled. Therefore, PNES must be considered in the differential diagnosis when managing patients with intractable epilepsy. Ictal behaviors are often inaccurately described by patients and lay observers in their verbal reports, although lay observers often seem better at recognizing previously occurring behaviors on review of events recorded with video-EEG than they are at describing habitual seizure behaviors (during a clinic interview). Video-EEG monitoring is the gold standard for clarifying the diagnosis when the individual’s habitual events are recorded. The finding in the recorded EEG that can usually confirm the diagnosis of PNES is no change in the EEG during PNESs, although artifacts may obscure the EEG, thereby preventing definitive determination of the unchanged nature of the waking or lightly drowsy recording. In some instances, a well-formed posterior dominant rhythm can be seen during the event (Figure 22). The EEG interpretations may be challenged by the fact that simple partial seizures often are associated with unchanged scalp EEG activities, and therefore a patient who reports a purely subjective event may have a nondiagnostic recording of such an event. We have discussed reasons that video-EEG recordings are more likely to be definitive in event diagnosis for patients who have normal or nearly normal interictal memory and cognition and who have global unresponsiveness and postictal amnesia for the event. Analysis of video-recorded behaviors can demonstrate behaviors that exclude diagnosis of epileptic events or organic nonepileptic events, and in any case it is important to establish that the individual’s habitual events have been recorded. The occurrence of a psychogenic event during video-EEG is of limited clinical signifi-

Figure 22. Psychogenic nonepileptic seizure. This electroencephalogram from a 51-year-old man with a history of shaking spells with unresponsiveness shows rhythmic artifact from body shaking. The patient became unresponsive. Immediately after the shaking, a well-formed posterior dominant rhythm is seen, which indicates the patient is awake at this time.
Pseudo-pseudoseizures

As mentioned above, video-EEG is very useful in diagnosing psychogenic events, with waking or lightly drowsy EEG activities that usually are normal (or unchanged from baseline) during a period of global unresponsiveness for which the patient subsequently is amnesic. Clinicians should be aware that there are a number of conditions that can be misdiagnosed with pseudoseizures. These conditions include parasomnias, syncope, paroxysmal dyskinesia, and epileptic seizures, in particular, those of frontal lobe origin. Many frontal lobe seizures have lower-amplitude ictal discharges than do complex partial seizures of temporal lobe origin, and frontal lobe seizures often are associated with vigorous and sometimes quite bizarre automatisms. When myogenic and kinesigenic artifacts significantly obscure EEG activities, no assumptions should be made about the nature of the obscured EEG; an ictal discharge may have been obscured. Other conditions, such as N-methyl-D-aspartate receptor autoimmune encephalitis, can present with a number of neuropsychiatric symptoms, such as episodic posturing and rhythmic movements. The absence of epileptiform activities on scalp EEG is a diagnostically useful observation when it occurs during a paroxysmal event with global impairment of consciousness (or of responsiveness-memory) and when the EEG is technically adequate (including relative absence of artifactual obscuration).

ICITAL RECORDINGS WITH INTRACRANIAL EEG IN EPILEPSY

Information obtained from EEG recorded with scalp electrodes may be insufficient in settings such as presurgical evaluation for epilepsy. Intracranial recording may provide critical information for the accurate localization of the epileptogenic zone. Depth electrodes and subdural electrodes are the most common intracranial electrodes used in clinical practice. Different types of electrodes are selected based on the questions being posed in an intracranial recording. All of the EEG rhythms observed in the scalp EEG recording can be seen in the intracranial recording if the electrodes are placed in the appropriate location. The volume of cortex that produces interictal spikes has been termed the “irritative zone,” and in many individuals this is a considerably larger volume than the “ictal onset zone” where earliest ictal discharges are recorded with intracranial electrodes. Intracranial recording of seizures differs significantly from scalp EEG. In scalp EEG recording, seizures can be observed in EEG only after they have spread to adjacent areas, and a 6 cm² area of cortex must be involved in the scalp EEG recording before changes can be observed. In intracranial recording, seizure onset can be observed in a very small region before the seizures spread (Figure 23). Hippocampal seizures can start with a different pattern such as repetitive spikes, theta to alpha activities, or high-frequency beta activities. Neocortical seizures usually start with high-frequency, low-amplitude beta activities.

BENIGN EEG VARIANTS AND ARTIFACTS THAT CAN SIMULATE INTRACRANIAL EEG ACTIVITIES

ARTIFACTS

One of the common pitfalls in EEG interpretation is to mistakenly identify artifacts as epileptiform activities or other abnormalities. Artifacts are signals that are mechanical or biological, but are noncerebral in origin. Artifacts can be classified as physi-
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Electrophysiological artifacts such as eye blinking or nonphysiological artifacts such as electrical interference from the power line. The following are commonly encountered artifacts in EEG recording:

- Eye blinking (Figure 24)
- Lateral eye movement (Figure 25)
- Eye flutter (Figure 26)
- Muscle artifact, including movements with chewing (Figure 27)
- Electrocardiogram
- Electrical interference from the power line
- Drip artifacts (due to catheters)
- Electrode artifacts (due to electrostatic and to salt bridge effects)

**BENIGN EEG VARIANTS**

For clinical practice in EEG reading, it is important to avoid “over-reading” that can potentially interpret normal variants as EEG abnormalities. These variants can be variations in rhythmic patterns or patterns with epileptiform-like morphology. Many of the epileptiform-like activities that were considered abnormal in the past are now considered as normal variants or of unknown clinical significance, such as wicket spikes, phantom spikes, and psychomotor variants. The following are commonly seen normal variants in EEG recording:

- Vertex sharp transients (Figure 28)
- Sleep spindles and K-complexes
- Wicket spikes (Figure 29)
- Phantom spikes (Figure 30)
- Rhythmic midtemporal theta (also called “psychomotor variant” or rhythmical theta bursts in drowsiness) (Figure 31)
• Slow alpha variant
• Small sharp spikes, or BETS (benign epileptiform transients of sleep)
• Mu rhythm (Figure 32)

SPECIAL APPLICATIONS OF EEG IN EPILEPSY

ELECTROCORTICOGRAPHY FOR SPIKE MAPPING DURING RESECTIVE EPILEPSY SURGERY

Interictal epileptiform activity recorded intraoperatively can, in theory, be used to adjust a partially predetermined margin of cortical resection in order to maximize the resection of epileptogenic cortex. Thus, preoperative recording of the patient’s habitual seizures with extracranial or intracranial electrodes could be used to determine the ictal onset zone, and intraoperative recording of interictal epileptiform activity could be used to expand the margin of resection to include spiking cortex in close proximity to the ictal onset zone (or in close proximity to the “standard” margin of resection for anterior temporal lobectomy). Alternatively, preoperatively recorded ictal onsets can be quite widespread, especially in partial epilepsies.
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of neocortical origin, and in some cases resection of only a portion of the apparent ictal onset zone can result in freedom from seizures. Subtotal resection of the electrographic ictal onset zone is usually performed in order to avoid resection of eloquent cortex that is included in the ictal onset zone, but interictal spikes recorded intraoperatively might also be used to delimit resection in cases of extensive ictal onset zones.

The conditions under which interictal spikes are recorded intraoperatively may influence their usefulness in shaping the margin of resection. Effects of sedative-anesthetic agents may make it easier or more efficient to record spikes, or may in some cases induce “false” spikes (as discussed above). Spikes recorded before excision often do not coincide with locations of post-resection (residual) spikes, implying that surgical manipulations can induce spikes at sites which ordinarily would not produce spikes. The practice of “chasing spikes” (ie, repeatedly resecting spikes that are recorded beyond the margin of resection even though the spikes were not recorded before the last round of resection-recording) can markedly enlarge the final volume of resection and appears to be on shaky ground conceptually.

Figure 28. Vertex sharp transients during sleep.

Figure 29. Wicket spikes. The sharp waves over the left temporal region are normal variants and should not be interpreted as epileptiform activities.

Figure 30. Phantom spikes. This is a form of normal variants and should not be over-interpreted as epileptiform activities.

Figure 31. Psychomotor variant (rhythmic midtemporal theta).
Surprisingly little is known about the efficacy of resecting spiking cortex that is found near the pre-planned margin of resection, perhaps because each surgeon-neurophysiologist team tends to act in a consistent fashion with regard to resecting or not resecting perimarginal spiking cortex. Some earlier investigators reported poorer seizure control in patients with postresection spiking on electrocorticography \(^{129,130}\) or no correlation between residual spikes and seizure outcome.\(^{131,132}\) More recently, a group in which temporal lobectomies were tailored (adjusted in resection margins) reported that postexcisional perimarginal spiking is significantly associated with more frequent postoperative seizures, but that 47% of patients without postoperative seizures had residual spikes and that 28% of patients with postoperative seizures did not have residual spikes.\(^{133}\) Another recent report from a center that uses standard (nonadjusted) temporal lobectomy margins indicated that persistence of spiking after resection did not predict recurrent seizures in individuals, but this finding was prognostically negative across the entire group.\(^{134}\) Interestingly, these investigators, who recorded intraoperatively with both epicortical and intracerebral electrodes, found that absence of preresection spiking carried a worse prognosis. In planning for any form of electrocorticography, whether for spike mapping or for functional mapping with DCES, preoperative consultation with the anesthesiologist is important to assure use of agents such as propofol that are unlikely to induce spikes or to lower the seizure threshold.\(^{135}\)

**ELECTROCORTICOGRAPHY WITH DCES FOR CORtical FUNCTION MAPPING DURING RESECTIVE EPILEPSY SURGERY**

The primary motor cortex is located on the gyrus just anterior to the central sulcus (the precentral gyrus), but the central sulcus is frequently difficult or impossible to reliably localize based on preoperative MRI or intraoperative visual inspection. In some instances, there is no functional primary motor cortex on the precentral gyrus due to early or late preoperative cerebral insult or less often due to apparent localization of primary motor cortex outside of an identifiable precentral gyrus. For these reasons, DCES is one of several techniques that are essential to localize this functional area. Application of 2 to 4 milliamperes of current to primary motor cortex typically induces clonic or tonic activity of the contralateral face or limb subserved by the particular portion of primary motor cortex. While some motor cortex areas also have sensory function, sequential lowering of stimulation amplitude can usually distinguish primary motor from primary somatosensory cortex (based on the function that persists at the lowest symptomatic level of stimulation). Negative motor responses are brief losses of postural tone or brief interferences with volitional motor activity that occur during and are limited to the period of DCES.\(^{136}\) Negative motor responses are characteristic of widespread areas of frontal and extrafrontal cortex that are not in the primary motor cortex.
cortex. Negative motor responses are often elicited at higher thresholds of stimulation intensity than are the tonic or clonic responses to stimulation over the motor strip.

Electrocorticographic recording of somatosensory evoked potentials (SSEPs) has also been used to localize the primary motor cortex. Multiple recording electrodes placed transversely across the suspected central sulcus typically will record cortical near-field potentials during upper or lower extremity sensory stimulation of the usual varieties used for SSEPs. The components N1 and P2 are highly restricted in distribution on electrocorticography (unlike their widespread scalp EEG distribution). The N1 and P2 components show phase reversal across the central sulcus when recorded anterior-posteriorly aligned recording electrodes. Thus, the gyrus immediately anterior to the phase reversal is the precentral gyrus, which should contain primary motor cortex. Movement-related potentials, including Bereitschaftspotentials and other premotor potentials, can also be recorded electrocorticographically in waking patients, but this observation has yet to be exploited clinically. A major advantage of both DCES and SSEPs for mapping of motor cortex is that either can be performed while the patient is under general anesthesia.

Efforts to characterize typical responses of the supplementary motor area to DCES have yielded somewhat variable results. In particular, classic observations of bilateral tonic posturing induced by unilateral supplementary motor area stimulation may in fact occur less commonly than do exclusively contralateral movements. Recording of movement-related potentials while the patient is awake may help to further define the supplementary motor area.

The major purpose of motor mapping is to define the hand area of the primary motor cortex, because resection of this cortex in a patient who has normal motor function preoperatively will result in irreversible loss of fine finger control. Other areas of the primary motor cortex have been resected without irreversible motor control deficits in some cases. Similarly, supplementary motor cortex and less specific motor-related cortex (areas at which negative motor responses are obtained) are routinely resected. In some cases it may be useful to localize these areas for purposes of obtaining agreement with ictal semiology in order to respect the apparent epileptogenic zone, as for example, in the typical supplementary motor area seizures.

Primary somatosensory cortex is normally located over the postcentral gyrus, with a general topography that often is similar to but rarely identical with that of the classic sensory “homunculus” (see Figure 33); the same is also true of the primary motor cortex and its “homunculus.” Mapping is quite similar to that performed for localization of primary motor cortex, with relatively low thresholds of 2 to 4 milliamperes for obtaining sensory responses. The patient typically reports some sort of simple sensation over the face or extremity contralateral to the area of localized stimulation. Because of potential suggestibility, some neurophysiologists prefer to apply placebo stimulations to demonstrate absence of any suspect reports in the particular individual. Electrocorticographic SSEPs can also be used to localize the primary sensory cortex on the same basis described above for motor mapping.

Penfield and Roberts first developed DCES for identification of language cortex based on the consistent observation that patients who were performing continuous naming tasks could have arrest of speech or other interference with naming during passage of current at a limited number of cortical sites. Interference with naming can...
occur at sites other than the classic Broca’s and Wernicke’s areas, and it is possible that naming is the best screening task for any localized areas of language-committed cortex. A variety of other tasks have been used for induction of errors by DCES as the basis of language mapping, including reading aloud, repetition, and comprehension of verbal or written material. When testing language function by DCES, it is important to repeat stimulations for consistency, since greater attention is required for most language processing than for mapping with sensory or motor tasks, and patients are frequently in mild or moderate discomfort during waking mapping. It is also important to exclude simple motor or sensory effects of stimulation, particularly during frontal lobe stimulation, by having the subject perform such tasks as repetitive alternating tongue movements that may be interfered with during stimulation (by positive or negative motor responses) even when no language processing is occurring. The thresholds at which language and other cognitive phenomena can be elicited by DCES may be as low as those associated with phenomena at primary motor and primary sensory cortex, but thresholds are usually much higher. It is important to attempt to stimulate up to 15 milliamperes before concluding that no detectable language function is represented in the area tested; at times adequate testing may be prevented by low afterdischarge thresholds that are
not significantly elevated by repetitive subthreshold stimulation at that site.

Mapping of Wernicke’s area is often considered the most important aspect of language mapping, because of evidence for persistent language dysfunction following intentional or inadvertent resection of Wernicke’s area. While Wernicke’s area is classically said to be located over the angular gyrus of the left hemisphere in left-hemisphere–dominant individuals, in fact there is great individual variability in the location of Wernicke’s area based on DCES. Wernicke’s area is frequently represented in posterior portions of the left superior temporal gyrus, but in a number of individuals it can be localized to more anterior locations of the superior temporal gyrus and even the middle temporal gyrus on the left (Figure 34 and Figure 35). This is of obvious importance given the location of the “standard” margin of resection used in anterior temporal
lobectomies,\textsuperscript{150} which varies among surgeons but can be further adjusted based on preoperative or intraoperative findings of language mapping. Ojemann and Dodrill\textsuperscript{151} found that if the margin of resection for left anterior temporal lobectomy fell within 2 cm of a site associated with replicable naming or speech arrest errors during continuous naming performance, a standard aphasia battery demonstrated increased errors 1 month postoperatively, while resections more than 2 cm distant were not associated with any postoperative changes on the aphasia battery. No effect of resection volume, preoperative language performance, or postoperative seizure control was apparent in this finding. Intraoperative language mapping in Ojemann’s series also demonstrated significant sex differences in typical localizations of Wernicke’s area, but little difference between sexes was noted in the strong tendency to have relatively small areas of language effect (2 cm\textsuperscript{2} or less).\textsuperscript{147} Others have reported more variable success in protecting language function with intraoperative mapping of parietotemporal cortex.\textsuperscript{152,153}

It is surprisingly difficult to demonstrate a Broca’s area as functionally distinct from primary motor cortex of the frontal opercular area, perhaps in part because a linguistically nonspecific finding of a negative motor response involving glossopharyngeal-laryngeal musculature will produce a speech arrest indistinguishable from that associated with an anterior aphasia.\textsuperscript{154} While frontal language areas are usually not resected, it has been reported that resections including left superior frontal language areas do not induce permanent language deficits.\textsuperscript{126}

The left basal temporal language area was first demonstrated by DCES\textsuperscript{155,156} and subsequently was confirmed by cerebral blood flow activation studies with PET and later with fMRI. Although this area typically is resected and its resection is not associated with permanent language deficits according to available information, there must be some residual concern regarding the safety of resecting this area. Patients with left temporal lobe epilepsy and left hemisphere language dominance frequently demonstrate naming deficits preoperatively,\textsuperscript{157} but with or without preoperative hyponomia they can demonstrate transitory, partially resolving, or significant permanent naming dysfunction beyond the degree of preoperative dysfunction following left temporal lobectomy.\textsuperscript{158} Since it is currently the standard of practice to resect any left fusiform gyrus and adjacent inferior temporal cortex which may harbor a basal temporal area, presumably it would be ethical to perform a double-blind controlled study of postoperative language function with and without resection of this area in individual’s demonstrating such an area by DCES. No report of such a study is currently available, however.

\textbf{DEVELOPING APPLICATIONS OF EEG IN EPILEPSY}

Clinical epilepsy-EEG experts must remain aware of relevant research trends in preparation for new therapies and diagnostic tools. The current interest in high-frequency oscillations recorded intracranially has been noted. Automated detection of “pre-ictal” EEG signals (Figure 36) also is an active area of epilepsy-EEG research. The potential benefits of devices and software identifying impending seizure discharges are apparent.\textsuperscript{159} Currently, such devices and software are not established for clinical use, but if and when they are, it is almost certain that clinical epilepsy-EEG experts will need to learn how to operate these new tools.
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Figure 36. Automated signal processing for seizure prediction. As shown in this schematic figure, qualitatively evident interictal EEG activities (during Observation) may change before onset of an electroclinical seizure (during Prediction), possibly permitting an acute abortive intervention such as deep brain stimulation before the seizure itself. Before ictal onset is qualitatively evident on intracranial electroencephalography data, a pre-ictal period of signal alteration may differ from other interictal observation periods, allowing for automated detection of a high probability of subsequent seizure onset. This pre-ictal signal alteration may or may not be qualitatively evident, but must differ quantitatively from preceding interictal observation periods to support automated detection. (Adapted with permission from Litt B, Echauz J. Prediction of epileptic seizures. Lancet Neurology 2002;1:22–30.)

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