The use of electrophysiology-based measures of brain activity dates back to the nineteenth century. In 1848, Du Bois-Raymond first demonstrated action potentials in nerves, and less than 30 years later, British psychologist Richard Caton described the electrical activity of the brain. In 1929, Hans Berger published the first report of the electroencephalogram (EEG) in humans, which in turn led to the first use of intraoperative EEG by Foerster and Altenberger in 1935. Beginning in the late 1930s, Wilder Penfield and Herbert Jasper further refined the technique of intraoperative EEG, demonstrating that it can be used to localize seizure activity during epilepsy surgery (Penfield & Jasper, 1954; see also Walker, Marshall, & Beresford, 1947).

In relation to questions of cortical function, tremendous advances in understanding were made by combining electrocorticographic (ECoG) recordings with electrical stimulation mapping (ESM)—the application of a brief electrical pulse to the cortex. For example, Penfield and Boldrey (1937) applied ESM to the motor cortex of awake human patients undergoing epilepsy surgeries. These studies produced a classic map for motor output referred to as the “motor homunculus,” a map indicating which regions of motor cortex control which motor effectors. Over 25 years later, Penfield and Roberts (1959) introduced language mapping as a technique to spare critical language areas during surgical resection of cortical tissue. Specifically, they reported that the stimulation of language cortex could produce aphasic-like errors, information that could guide the extent of the surgical resection (Ojemann & Whitaker, 1978). Finally, in the 1970s, Ojemann and colleagues used ESM to map various cognitive functions (e.g., language and memory) in awake patients undergoing epileptic foci and tumor resections (Rao et al., 1995). Today, the technique is employed clinically to guide tissue resections and used experimentally to understand the neural mechanisms underlying cognitive function.

Methods of Intracranial Recording

Stereoelectroencephalography
Stereoelectroencephalography concerns recording electrical activity from electrodes inserted beneath the cortical surface. The stereotactic method was first used to investigate
functioning of the thalamus and hypothalamus in patients with petit mal epilepsy (Spiegel & Wycis, 1950, 1951). Since its advent, stereoelectroencephalographic—or depth—recordings have been done with linear, multicontact arrays, and continue to be used for the localization of epileptic seizure activity. The electrodes are monitored within the subject for days to weeks, during which time researchers can do additional cognitive experiments. In terms of the electrode metals used, it is important to note that many metals when left in the brain for periods greater than a day can cause inflammatory reactions. For instance, cobalt, copper, nickel, and vanadium cause toxic reactions (Wiese, 1999); platinum, silver, chlorided silver, and tungsten can cause reactions when left in for a period of weeks to months (Hscher, Sayre, & Bickford, 1957; Robinson & Johnson, 1961; Cooper & Crow, 1966; Cooper, Ossettow, & Shaw, 1980). The thin wire used to make contemporary intracerebral electrodes is generally encapsulated with Teflon or some other type of nontoxic enamel (Cooper, Ossettow, & Shaw, 1980).

In relation to ERPs, Halgren and colleagues have successfully used stereoelectroencephalography to better localize the origins of various scalp recorded evoked potentials (Halgren et al., 1980; Halgren et al., 1995). For example, they have demonstrated that the scalp recorded P300 is a product of multiple cortical generators (Baudena et al., 1995; Clarke, Halgren, & Chauvel, 1994a, 1999b; Halgren et al., 1995a, 1995b; Halgren, Marinkov, & Chauvel, 1998). They propose that the brain has developed a strategy in which it recruits all potentially useful regions in order to complete a task, even though the probability that each region will contribute to the immediate task is low. In turn, this widespread activation of multiple parallel-processing systems is assumed to facilitate interactions with the natural environment, where it is beneficial to rapidly identify and evaluate an event so that an adaptive response can be made (Halgren, Marinkov, & Chauvel, 1998). Importantly, these studies demonstrate how intracranial recordings can contribute to both psychological and neuroscientific theory.

Critically, stereoelectroencephalographic methods continue to evolve. Halgren and colleagues have recently developed a thumbstick-like multielectrode with intercontact distances of 75-200 μm (Ulbert et al., 2001). This has allowed for the exploration of laminar patterns of cortical activity, including the firings of single units. Similarly, intracranial single-unit recordings in the medial temporal lobe and basal ganglia have provided important insights into memory and visual perception (Ojemann & Schoenfield-McNeill, 1999; Kreiman, Koch, & Fried, 2000), as well as motor control (Brown et al., 2002). Researchers have also applied stereoelectroencephalographic methods to questions of functional connectivity. For instance, depth electrode recordings have revealed β-band oscillatory synchrony between extrastriate regions during short-term memory maintenance (Tallon-Baudry, Bertrand, & Hscher, 2001).

**Electrocorticography**

Electrocorticography (ECoG) concerns the recording of electrical potentials directly from the cortical surface. In this domain, there are two main methods for ECoG recordings (Reid, 1989): (1) individual movable electrodes (IMEs), and (2) arrays of electrodes embedded in a flexible elastic sheet. The following sections detail the particulars of each electrode type and its uses.

**Individual Moveable Electrodes** Individual Moveable Electrodes are typically ball-shaped electrodes made of silver, platinum, or carbon, and are attached to an apparatus affixed to the skull (figure 14.1, plate 8). An important use of these recordings is to monitor cortical after-discharges during electrical stimulation mapping (ESM). Ojemann and colleagues have conducted a limited number of studies using these intraoperative recordings for the investigation of language related potentials (Fried, 2001).

**Figure 14.1**
The picture depicts a typical electrode mounting apparatus, the horseshoe-shaped cortical crown. The carbon ball electrodes can be seen at the end of the white wires connected to the crown. The numbers tag the locations of cortical stimulation during language or motor mapping. (See plate 8 for color version.)
**Figure 14.2**

Essential language sites in 117 patients. The number within the circle is the percentage of patients with an essential language site in that region. The number above the circle gives the number of patients for whom that region was tested. (Courtesy of the *Journal of Neurosurgery*, in Ojemann et al., 1989.)

Ojemann, & Fetz, 1981; Ojemann, Fried, & Lettich, 1989). Most notably, they mapped essential language sites in 117 patients and demonstrated that, although there is some concentration around traditional Broca’s and Wernicke’s areas, there is remarkable intersubject variability in the number and location of essential language sites (Ojemann, Fried, & Lettich, 1989) (figure 14.2).

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**Silastic Sheets**  
The great majority of published ECoG studies of cognitive phenomena employ Silastic sheets, which are subdural arrays of electrodes imbedded in a flexible, transparent sheet (figure 14.3). When laid on the surface of the patient’s brain, the sheet takes up the convexity of the cortex. Almost invariably, these electrodes are made of platinum-iridium or stainless steel, have a diameter of ~3 mm, and have an interelectrode spacing of about 1 cm.

The most frequently studied region of the brain using Silastic sheets has been the sensorimotor system, where several centers have studied evoked potentials and spectral activity (Baumgartner et al., 1991, 1992; Crone et al., 1998a, 1998b). An interesting application of this research is the development of a direct brain interface for neuroprosthetic motor control in paralyzed individuals (Levine et al., 2000). Outside of the sensorimotor cortex, a small number of studies have used subdural ECoG arrays to study visual processing (Amway et al., 1997), auditory processing (Crone et al., 2001a), or language (Nobre, Allison, & McCarthy, 1994; Nobre & McCarthy, 1995; McCarthy et al., 1995; Hart et al., 1998; Crone et al., 2001b).

**Methodology**

**Recording**

Often taking place in the operating room environment, ECoG recordings face a number of challenges: (1) electromagnetic interference from operating room equipment, (2) a nonsterile reference electrode, (3) recording of far-field potentials, and (4) the influence of anesthetic agents, which can alter the EEG recordings. Consequently, anyone undertaking ECoG recordings should consider these issues carefully when designing, analyzing, and interpreting experiments.

**Electromagnetic Interference**

The operating room is a haven of electromagnetic interference due to the fluorescent lighting and the abundance of electric and magnetic equipment (e.g., heart monitors, computers, MRI scanners). Three techniques that can facilitate the acquisition of relatively noise-free data are low impedance electrodes, a differential amplifier with good common mode rejection (at least 100 dB), and proper grounding and shielding of equipment and cables.

For an amplifier to perform maximally, electrode impedances should be kept at a value less than the amplifier’s input impedance by a factor of 100 (Picton et al., 2000).
Impedance and noise are directly related. That is, the higher the electrode impedance, the more likely that electromagnetic fields will contaminate the recordings (Picton et al., 2000). Furthermore, impedances should be kept constant across electrodes. Unequal electrode impedances will reduce the ability of the differential amplifier to reject common mode signals (Legatt, 1995; Picton et al., 2000). It is also important to use electrodes that are composed of the same material; using dissimilar metals can result in DC offsets between recording channels.

A differential amplifier with an excellent common mode rejection feature (e.g., a typical system on the market has a rejection ratio of 1000:1, or 100,000:1, reduction, in 60-Hz noise) is beneficial because it allows for the elimination of signals occurring in phase at each of the electrodes. Specifically, each active electrode will pick up signals that are both in and out of phase with respect to the reference electrode. However, based on the properties of a differential amplifier, whatever is in phase with the reference electrode—that is, the common signal—will be subtracted out. Furthermore, common mode rejection eliminates the data distorting that can occur with 60-Hz notch filters, which produce a damped oscillatory response when presented with a transient input (Cooper, Osselton, & Shaw, 1980).

Proper grounding and shielding techniques can also help reduce unwanted noise. One very basic step is to limit the length of all cables used and shield them thoroughly. Note that in order to activate a shield, it needs to be grounded. If the operating room has a designated ground, connect the shield wire to that terminal. If not, attach the shield wire to the amplifier chassis. As well, keep the amplifier and any lead box cables far away as possible from any AC cords or other electronic devices.

**Noninvasive Reference Electrode** In a monopolar electrode arrangement or referential montage, voltage is recorded from an epicortical electrode (i.e., the active electrode) relative to an electrode placed approximately several centimeters away (i.e., the reference electrode). The reference electrode might be placed on the pia mater, on the dura mater, on the scalp, or on some other skin surface, such as the nose or neck. In any case, the reference is considered to be a neutral reference (i.e., a “silent reference” or “inactive reference”), such that any activity recorded on that channel can be ascribed to activity occurring at the site of the active electrode.

In reality, however, the ideal of a truly neutral reference is never accomplished in real recordings, due to contributions from electrically nearest neural or muscle activity. Reference electrodes on the pia mater, dura mater, or scalp will ultimately introduce neural activity into the channel, and reference electrodes on the scalp, nose, neck, or needle electrodes inserted into muscle will reflect muscle activity. Furthermore, with epicortical or epidural reference electrodes it is important to have them placed as far away from blood vessels as possible, which can also introduce unwanted artifacts into the EEG. As with scalp recordings, reference electrodes on the scalp or nose will also include ocular artifact from the corneomental dipole.

One method to determine the most silent reference is to record from numerous electrodes, create ERPs by averaging across trials, visually inspect the waveforms for the most silent electrode, and then re-reference off-line to that electrode. A predicted model of the original reference can also be created in order to obtain a better understanding of the signal. However, this method does not eliminate the problems inherent to a noninvasive reference, due to the fact that with differential amplifiers the original recording will always include an influence from the original reference electrode. As a consequence, its effects are not completely eliminated. But it does allow for some reduction in reference artifact contamination.

Crone et al. (2001a) argue for the use of a common average reference in analyzing ECoG data. The technique involves taking the average potential from all nonartefactual channels and then subtracting the result from the potential in each channel. This method allows for a reference independent calculation. The aforementioned calculation, however, does not allow for an evaluation of the original reference. To evaluate the activity at the original reference site, divide the sum of all channels by the number of all channels plus one (Dien, 1998). Nonetheless, it is important to note that with limited epicortical electrode coverage, one cannot assume that the common average reference can approximate an inactive reference. The technique is based on scalp EEG, which generally involves denser coverage, and satisfies the assumption that the signals—obtained from multiple scalp locations—relative to the average reference will approximate the true voltage over the head, namely average to zero (Bertrand, Perrin, & Pernier, 1985; Dien, 1998). Specifically, because the brain does not create nor destroy charge, its current sources (regions with net current outflow into the extracellular space) and sinks (regions with net current inflow into the neuron) should be equivalent. Hence, the potentials observed at the surface of the cortex or scalp (i.e., a spherical volume conductor) should average to zero (Bertrand, Perrin, & Pernier, 1985). As such the common average reference should act as a supplement to the common reference analysis. For a more detailed discussion of the common average reference, see Dien 1998.

**Far versus Local-Field Potentials** Relative to scalp-recorded ERPs, the advantage of ECoG recordings is their greater spatial localization of signal sources, which stems from recording local-field potentials on the cortical surface that are unrecordable on the scalp surface. On the other hand, far-field potentials—which comprise all cortical activity recorded on the scalp surface—arise from distant voltage sources, such as the corneomental dipole, subcortical dipoles, or distant cortical dipoles. Because the potential of a single dipole falls off in strength with the square of the distance from the
dipole, the contribution of far-field potentials to ECoG recordings are considered to be weak compared to the local-field potentials arising directly beneath or in the near vicinity of the recording electrode. Also, unlike surface-recorded ERPs, the reference electrode is often in relative proximity to the recording electrode, so it would tend to cancel out far-field effects.

Nonetheless, far-field potentials often appear in ECoG recordings. Recordings in animals from the crown of a gyrus can show far-field effects from the parts of the gyrus buried within the sulcus (e.g., Pellegatti et al., 1987). Our own data from peri-Sylvian areas of humans show auditory potentials originating from the superior temporal plane buried within the Sylvian fissure (figure 14.4) (Soltani et al., 2003).

**Effects of Anesthetic Agents** Anesthetic agents exert their effects by altering cerebral metabolism, which in turn can affect the EEG by either exciting or depressing it (Sloan, 1998) (table 14.1). As a further complication, each anesthetic agent alters the evoked response differently. Hence, general knowledge of commonly used anesthetics and their effects on intraoperative electroencephalography is beneficial. As a rule of thumb, halogenated inhalational agents decrease the amplitude and prolong the latency of evoked potentials (EPs); nitrous oxide prolongs the latency and decreases the amplitude of cortical EPS; barbiturates increase beta frequency activity in the EEG, decrease the amplitude and increase the latency of EPS; ketamine either does not effect EPS or it increases their amplitude; benzodiazepines increase beta activity, decrease EP amplitude, and have no effect on latency; etomidate causes an increase in both amplitude and latency of EPs; propofol decreases the amplitude of EPS but has a rapid recovery after termination; narcotics reduce EP amplitude; and neuromuscular blockers (muscle relaxants) demonstrate no significant effect on EPS (Sloan, 1998). For a more detailed review of the effects of anesthetic agents, see Sloan 1998.

**Table 14.1**

<table>
<thead>
<tr>
<th>Agents</th>
<th>EEG Effects</th>
<th>EP Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halogenated Inhalational</td>
<td>Varies based on agent used (see Sloan, 1998)</td>
<td>Decrease amplitude increase latency</td>
</tr>
<tr>
<td>(e.g., desflurane, enfurane,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>halothane, isoflurane)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrous Oxide</td>
<td>If used alone produces high frequency activity (&gt;30 Hz) frontally</td>
<td>Decreases amplitude increases latency</td>
</tr>
<tr>
<td>Barbiturates</td>
<td>Increase beta activity</td>
<td>Decrease amplitude increases latency</td>
</tr>
<tr>
<td>Ketamine</td>
<td>Produces high amplitude theta activity and increase beta activity</td>
<td>Increases amplitude</td>
</tr>
<tr>
<td>Benzodiazepines</td>
<td>Low doses: Produces frontal beta activity with a decrease in alpha activity</td>
<td>Decrease amplitude No effect on latency</td>
</tr>
<tr>
<td>Etomidate</td>
<td>Dose-dependent depression</td>
<td>Increases amplitude</td>
</tr>
<tr>
<td>Propofol</td>
<td></td>
<td>Decreases amplitude, with rapid recovery upon termination</td>
</tr>
<tr>
<td>Muscle Relaxants</td>
<td>No effect</td>
<td>No effect</td>
</tr>
</tbody>
</table>

Data gathered from Sloan (1998).

of cortical EPS; *barbiturates* increase beta frequency activity in the EEG, decrease the amplitude and increase the latency of EPS; *ketamine* either does not effect EPS or it increases their amplitude; *benzodiazepines* increase beta activity, decrease EP amplitude, and have no effect on latency; *etomidate* causes an increase in both amplitude and latency of EPS; *propofol* decreases the amplitude of EPS but has a rapid recovery after termination; *narcotics* reduce EP amplitude; and *neuromuscular blockers* (muscle relaxants) demonstrate no significant effect on EPS (Sloan, 1998). For a more detailed review of the effects of anesthetic agents, see Sloan 1998.

**Data Analysis**

The analysis of ECoG data has many parallels to the analysis of scalp-recorded EEG. However, important differences exist as well, including both issues of method and interpretation. In the following sections we consider the particulars of artifact rejection, signal averaging, and time frequency analysis as they pertain to ECoG data.

**Artifact Rejection** Like deriving scalp-recorded ERPs, eliminating of artifact from the EEG data set is critical for intracranial ERPs. Generally there are four sources of artifact:
(1) EEG equipment (not discussed here; for a review, see Cooper, Osselton, & Shaw, 1980), (2) electromagnetic noise in the recording environment, (3) noisy electrodes and leads, and (4) noncerebral physiologic potentials. The rejection of such artifacts can best be accomplished with computer algorithms in conjunction with the visual inspection and the manual rejection of contaminated trials.

External electrical interference can be a serious contaminant of intraoperative data. The sources of the problem stem from electrostatic, electromagnetic, and radio-frequency pulses that can be traced to the abundance of electronic equipment in the operating room. We discussed solutions for reducing the electrical interference above.

Nonetheless, the most effective way to remove the remaining electrical noise (e.g., 60-Hz line noise) involves conducting off-line low- and high-pass filters aimed at removing the contaminant frequency (see also Picton, Lins, & Scherg, 1995).

Artifacts from electrodes and leads generally result from poor contact between the electrode and the patient’s cortex. The most obvious solution is to request that the electrode be reapplied to the brain. If, however, this is not possible, the electrode can be dropped either on- or off-line. Because the currents needed to measure electrode impedances are very low, researchers can use these measures to identify bad electrode contacts prior to recording. Furthermore, the contact between the electrode and the cortex may at times be disrupted by the surgical team and thereby cause the EEG amplifier to saturate. In recordings involving stimulation mapping, the current applied to the cortex can cause nearby electrode channels to saturate. Saturation can be prevented off-line with a gate that pauses the recording, or off-line with computer algorithms designed to remove those trials that are affected by and/or recovering from saturation. The most basic algorithm involves comparing each segment of the EEG time series with a maximum voltage threshold, and discarding that segment of the data when this threshold is exceeded (see chapter 5 of this volume).

The most common artifacts in EEG recordings are those that arise from the patient. Fortunately, unlike with scalp recordings, in the intraoperative setting eye movement, blink, and muscle potentials do not affect the EEG (an exception to this rule would result from an ill-placed reference electrode). This, however, does not mean that intraoperative data is free from physiologic artifact. For instance, the ECoG does contain a pulse artifact. When the brain is exposed, clear pulsations are visible with each heartbeat; this can cause a pulse artifact in the ECoG and is especially problematic if it arises in the reference electrode. Specifically, the electrodes rest on the surface of the brain and thereby move relative to the cortex. As with surface EEG recordings, creating a stable metal/liquid interface can minimize this artifact. One method for creating a stable interface, as Cooper, Osselton, and Shaw (1980) suggest, is “by using cotton wicks, soaked in saline solution, which rest on the brain surface and connect to wires supported by a clamp affixed to the skull.” A second method requires interfacing the EKG machine with the ECoG acquisition machine, and directly recording the patient’s heartbeat, so that the pulse artifact can be estimated and removed off-line. Finally a third involves filtering the data off-line with a high-pass filter set high enough to remove the patient’s heart rate (~2 Hz, depending on heart rate and filter roll-off), but not so high that it removes potentially interesting slow waves (probably no higher than ~4 Hz).

Anesthetics can also introduce artifacts into the data, and can be difficult to interpret and reject. As table 14.1 details, a general understanding of the various anesthetics and their effects can facilitate the process. The best rejection method in this situation involves visually inspecting the data and manually removing those trials that demonstrate abnormal (or anesthetically induced) patterns of activity. Depending on the frequency of the artifact, high-pass filtering may also help.

Signal Averaging The most basic method for analyzing ECoG data is to derive ERPs, which are simply the time-locked averages across many trials. The time-locking is typically done to a stimulus, such as an auditory tone, and the resulting ERP contains a series of positive and negative voltage fluctuations from the pre-stimulus baseline, termed components. Note, however, that the ERPs recorded from the cortical surface are much greater in amplitude than those recorded from the surface of the scalp. Indeed, single-trial event-related responses can sometimes be seen in ECoG data. However, in our own experience, the signal-to-noise for corticaly recorded ERPs is still too low such that several tens of trials are needed to obtain a stable waveform in the ERP (figure 14.5).

Scalp-recorded ERPs provide a noninvasive measure of the temporal course of various cognitive processes, but they do lack in spatial resolution. That is, relative to the latest brain imaging techniques such as fMRI, ERPs do not provide adequate information regarding the neural generators of a particular brain potential. Nonetheless, high-density recording arrays in conjunction with sophisticated data analysis techniques have enabled researchers to extract some information regarding the location of various neural generators. For instance, researchers have employed dipole source localization techniques, wherein they seed dipoles, located in a region thought to be involved in the generation of a particular ERP component, into a source modeling algorithm. The algorithm, in turn, provides information regarding the scalp distribution of the seeded dipoles. If the distribution significantly resembles (or explains) that of the component in question, then one can conclude that the chosen region is a potential generator of that ERP component. This is also known as the forward solution. Note there is also an inverse problem, which states that scalp distribution cannot effectively be used to localize (or determine) neural generators, because there are an infinite number of solutions (or dipole positions) that can potentially sum to give rise to each scalp-recorded distribution (for a review of these issues, see chapter 7 of this volume).
Like scalp EEG, intracranial EEG has very high temporal resolution, but unlike scalp EEG, it also has very high spatial resolution. The spatial resolution of intracranially recorded ERPs is effectively limited by electrode size and spacing, and as such the technique can identify local ERP generators (Halgren, Marinovic, & Chauvel, 1998). In this method, if a locally recorded ERP component is much larger in amplitude than in neighboring structures, and it changes in polarity over short distances, then one can conclude that the structure in question is a generator of the observed ERP component (see figure 14.4).

Finally, in interpreting the waveforms one should consider the stimuli used to elicit the ERP and the properties of the scalp-recorded ERP (i.e., amplitude, latency, and spatial distribution) in order to obtain a clear understanding of what the intracranially recorded ERP represents. As a general rule of thumb, earlier components are most commonly associated with sensory events and the later with more cognitive events. The amplitude generally provides information regarding the extent of the neural activation, the latency the onset of the activation, and the scalp distribution the underlying activity or pattern of brain activation (Friedman, Cycowicz, & Gaeta, 2001).

**Time-Frequency Analysis** Time-frequency analysis allows for the investigation of the event-related spectral perturbations of the brain (e.g., gamma activity or 40 Hz). For instance, animal electrophysiological studies have demonstrated that synchronized brain activity in the gamma frequency range may be the correlate to feature binding (Gray et al., 1989). In line with the animal findings, induced gamma activity may correlate with feature binding in humans (Müller et al., 1996). Researchers can also use event-related coherence measures to investigate functional connectivity between various brain regions. For example, by examining how the gamma activity observed in two different brain structures "correlate" with one another.

The same time-frequency methods used in scalp EEG, mainly moving-window fast Fourier transforms (FFTs) and wavelet-based methods (see chapter 11 in this volume), are used for intracranial data. Once again by bypassing the low-pass filter characteristics of the skull, intracranial recordings allow for the examination of high frequencies. Using subdural electrodes, Crone et al. (2001a) reported high-frequency gamma activity (∼80–100 Hz) in the auditory cortex during a phoneme discrimination task. In a simple intraoperative mismatch negativity (MMN) task, we also acquired high-frequency gamma activity (70–170 Hz) to deviant tones, but when we conducted the same task using scalp recorded EEG we did not observe the high-frequency activity (70–170 Hz). Finally, intracranial recordings have also provided information on high-frequency "ripples" (100–500 Hz) in hippocampal and epileptic human cortex (Staba et al., 2002a, 2002b), and have shown that successful memory performance is accompanied by rhinal-hippocampal gamma band coupling (Fell et al., 2001). Hence, those undertaking time-frequency analyses should examine the higher frequencies as well.
Unless 60 Hz is a major recording issue, the amplifier low-pass filter (LPF) should be set higher for ECoG than what is typical of scalp recordings.

Applications

Intracranially recorded EEG can be applied to many of the same questions of cortical function addressed with scalp-recorded EEG, albeit with a higher degree of certainty regarding the loci of EEG signal sources. However, there are also questions that may be tractable only with intracranial recordings. Here we consider two questions uniquely addressed via intracranial methodology.

The Effect of the Skull on EEG
In relation to scalp-recorded EEG, the skull is thought to act as a low-pass filter. Toward validating this assumption, Pfurtscheller and Cooper (1975) investigated the low-pass properties of the skull by recording simultaneous ECoG and EEG in a single patient. Specifically, they directly applied sinusoidal voltages of varying frequencies through two IMEs, and measured the responses at the remaining IMEs and on the surface of the scalp. Applying this method, they found that the low-pass characteristics of the skull (as measured by scalp EEG) are due to a decrease in signal coherence across space as signal frequency increases. Thus, as signal frequency increases, there is a reduction in the degree to which signal phases align and thus the signals at higher frequencies tend to cancel out. In short, amplitude in the scalp EEG is a function of amplitude plus coherence in the ECoG, and at the scalp surface both amplitude and coherence decrease with frequency. In further comparing scalp EEG to cortical ECoG, considerable differences in signal spectra can be observed in ECoG electrodes spaced just millimeters apart, which is not generally the case for scalp-recorded EEG (Cooper et al., 1965).

The Size of Functional Units in Cortex
A second question relevant to intracranial recordings concerns elucidating the size of functional units in cortex. The question is particularly amenable to the analysis of synchrony in EEG frequency bands. The local domain of EEG synchrony, at least for gamma rhythms, is about 1 cm² (Menon et al., 1996, discussed further below). In conjunction from converging evidence from other domains, this suggests that the size of specialized cortical “modules” is on the order of a square centimeter or so. The techniques used to discover the locations and overall functions of these modules might be termed “mesoscopic.” A technique that looks at spatiotemporal patterns of activity within a module in order to determine how its primary computational units (cortical columns of the order of 1 mm in diameter) interact might be termed “mesoscopic.”

Clearly, the uses of ECoG are essentially macroscopic, because the diameter and spacing of the electrodes are such that 1 cm² regions of cortex are sampled, and many tens of cortical columns are sampled beneath each electrode. However, Walter Freeman and Helmuth Petsche pioneered electrocorticography with grids of more closely spaced electrodes in animals in the 1970s. Both have argued convincingly for mesoscopic imaging (Petsche, Pockberger, & Rappelberger, 1982, 1984; Freeman, 2000). For example, Petsche studied penicillin-induced seizure activity in rabbits using a 4 × 4 grid of electrodes with 0.3 mm diameter and spacings of 1 or 2 mm (Petsche, 1976; Petsche, Pockberger, & Rappelberger, 1982). He modeled synchronization as arising from interactions of many elementary generators, each producing a unique signal. These generators are about 1 mm in diameter and probably correspond to cortical columns.

In humans, Freeman and colleagues have also examined synchrony of gamma activity and the spatial resolution of its underlying generators. Menon et al. (1996) used a standard silastic sheet with 1 cm spacing between electrodes to look for domains of spatially correlated gamma activity, as had been previously identified in animals. They reported negative results, suggesting that domains of locally correlated gamma activity existed on spatial scales smaller than 2 cm². They concluded that a denser array of electrodes, with spacings no greater than 0.5 mm, would be needed to study patches of local correlation. In a second study (Freeman et al., 2000), a new array was created that had closer spacings between electrodes. The new array had 0.1 mm diameter stainless steel electrodes embedded in a linear arrangement at an interelectrode spacing of 0.5 mm. The results of the study were consistent with a 1 cm² size for the domains of local gamma synchrony, but the linear array left other analyses wanting. They concluded that the optimal array would have “an electrode interval of 1.25 mm and an 8 × 8 spatial window of at least 10 mm.” In sum, mesoscopic imaging in humans awaits such an electrode array.

Conclusion

Even though intracranial EEG provides excellent temporal and spatial resolution, it is still not without problems. For example, the technique does not employ healthy, normal working brains. As well, intracranial investigations are limited to recording from restricted brain regions. That is, the method provides information relating to a limited number of brain regions that have not necessarily been identified through experimental requirements. Fortunately, however, imaging techniques, such as functional magnetic resonance imaging (fMRI), provide excellent spatial resolution. As such, neuroimaging techniques can complement the intracranial findings by allowing for noninvasive investigations of the entire healthy human brain. Indeed, lesion and imaging studies have revealed a mosaic of interacting cortical modules that specialize in different functions. The technique thus offers the unique opportunity to look at the patterns of activity within these modules to better understand how they perform their
specialized task. Proper analysis of the high-density data should also allow for clarification of issues relating to far-field effects and activity at the reference electrode.

Another lucrative possibility is to perform functional connectivity analyses on preoperative fMRI data sets, and then position two high-density electrode arrays over potentially intersecting regions. The technique may allow for the observation of interareal synchronization between regions identified as functionally connected in fMRI (Bressler, 1995; von Stein, Chiang, & König, 2000). ESM mapping could also be used to identify regions that interact during a certain task or function. The spatial resolution of a high-density electrode array will also allow for testing broader hypothesis of neural transient interactions and interareal mutual information, of which interareal synchronization is but a subset (Irishon, 1995, 1997). Such studies will undoubtedly lead to new insights concerning neocortical dynamics and information processing.

Note

1. Although these electrodes technically sit on top of the pia mater and some arachnoid, in the literature they are typically referred to as “epicortical.”

References


ERPs and Intracranial Recordings


