Introduction

In 1848, Du Bois-Raymond demonstrated action potentials in nerves and less than 30 years later in 1875 British psychologist Richard Caton described the electrical activity of the brain. Most relevant to this text, 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 Alternberger in 1935. Beginning in the late 1930s and continuing through the 1950s, Wilder Penfield and Herbert Jasper further refined the technique of intraoperative EEG and in so doing demonstrated that it can be used to localize seizure activity during epilepsy surgery (Penfield and Jasper, 1954).

As a historical note, electrocorticographic (ECoG) recordings in combination with electrical stimulation mapping (ESM) -- the application of a brief electrical pulse to the cortex -- have led to tremendous neuroscientific advancements. For instance, Penfield and Boldrey (1937) applied ESM to the motor cortex of awake human patients undergoing epilepsy surgeries. The studies produced a classic map for motor output referred to as the
"motor homunculus." Over 25 years later, Penfield and Roberts (1959) introduced language mapping as a technique to spare critical language areas. Specifically, they reported that the stimulation of language cortex could produce aphasic like errors, and the information, in turn could be used to guide the extent of the surgical resection (Ojemann and 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 experimentally to understand the neural mechanisms underlying cognitive functions.

With that brief historical introduction we now turn to the primary focus of this chapter, which is to describe the various types of intracranial recording techniques and to introduce some of the methodological issues that scientists will encounter when employing the method. Specifically, the chapter will describe stereoelectronencephalographic and electrocorticographic (ECoG) techniques, and the issues surrounding the recording, the analysis, and the interpretation of intracranial EEG data. When possible cortical recordings
will be compared to scalp recorded event-related potentials (ERPs).

**Methods of Intracranial Recording**

**Stereoelectroencephalography**

Although the chapter will primarily focus on electrocorticographic (ECoG) recordings of the cortex a brief review of stereoelectroencephalography (depth recordings) will be presented. The stereotactic method was first used to functionally investigate the thalamus and hypothalamus in patients with petit mal epilepsy (Spiegel and Wycis, 1950, 1951). Since its advent stereoelectroencephalographic recordings have been done with linear, multi-contact 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 additional cognitive experiments can be done. 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 should not be employed, because they are known to cause toxic reactions (Wieser, 1999), and platinum, silver, chlorided silver, and tungsten can all cause
reactions when left in for a period of weeks to months (Fischer, Sayre, and Bickford, 1957; Robinson and Johnson, 1961; Cooper and Crow, 1966; Cooper, Osselton, and Shaw, 1980). The thin wire used to make the intracerebral electrodes is generally encapsulated with Teflon or some other type of non-toxic enamel (Cooper, Osselton, and Shay, 1969).

Eric Halgren and colleagues have successfully used stereoelectroencephalography to better localize the origins of various scalp recorded evoked potentials such as the P300 (Halgren et al., 1980; Halgren et al., 1995). For instance, Halgren and coworkers have demonstrated that the scalp recorded P300 is a product of multiple cortical generators (Baudena et al., 1995c; Clarke et al., 1999a, 1999b; Halgren et al., 1995a, 1995b, 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. They further argue that this widespread activation of multiple parallel-processing systems proves advantageous in the natural environment where it is necessary to rapidly identify and evaluate an event so that a response can be
quickly initiated or withheld, and, thus, increase the probability for survival and reproduction (Halgren et al., 1998). These studies demonstrate how intracranial recordings can contribute to both psychological and neuroscientific theory.

Halgren and colleagues have also recently developed a thumbtack like multielectrode with intercontact distances of 75 to 200 μm (Ulbert et al., 2001) and have begun exploring laminar patterns of cortical activity, including the firings of single-units (Ulbert et al., 2001). Note that intracranial single unit recording in the medial temporal lobe and basal ganglia has provided important insights into memory and visual perception (Ojemann and Schoenfield-McNeill, 1999; Kreiman, Koch, and Fried, 2000) as well as motor control (Brown et al, 2002). Finally, another important recent study using chronically indwelling depth electrodes reported β-band oscillatory synchrony between extrastriate regions during short-term memory maintenance (Tallon-Baudry et al., 2001).

Electrocorticography

As previously mentioned, electrocorticography (ECoG) -- the recording of electrical potentials directly from
the cortical surface\textsuperscript{1} -- was introduced in the 1940’s for mapping seizure activity in epilepsy surgery (Walker et al., 1947; Penfield and Jasper, 1954), and this continues to be by far its most common clinical use. There are two main methods for ECoG recordings (Reid, 1989): arrays of individual movable electrodes (IMEs) and subdural arrays embedded in a flexible silastic sheet. IMEs are typically ball-shaped electrodes made of silver, platinum, or carbon and attached to an apparatus affixed to the skull.

\hspace{1em} \text{Insert Figure 1 Here}

An important use of these recordings is to monitor cortical afterdischarges 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 et al., 1981; Ojemann et al., 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, the main result is the remarkable amount of
intersubject variability in the number and location of essential language sites (Ojemann et al, 1989).

The great majority of published ECoG studies of cognitive phenomena employ subdural arrays of electrodes imbedded in a flexible, transparent silastic sheet which when laid on the surface of the patient’s brain 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 1 cm. The most frequently studied system is the sensorimotor system, where evoked potentials and spectral activity have been studied by several centers (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 (Arroyo et al., 1997), auditory processing (Crone et al., 2001a), or language (Nobre et al., 1994, 1995; McCarthy et al., 1995; Hart et al., 1998; Crone et al., 2001b).

All of the studies mentioned so far for surface ECoG recordings have used interelectrode spacings of 1 cm. With a sufficient number of electrodes in the silastic array, these recordings act as an improved scalp recorded EEG. The improvements include better spatial and frequency resolution without the skull and near absence of eye and muscle artifacts. The skull is thought to act as a low-pass filter. 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 at the scalp. They discovered that the low-pass characteristics of the scalp EEG are due to the lower tendency for coherence, across space, as frequency increases. Thus, the phases are not as likely to be aligned and 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 both of these are lower for higher frequencies. In this manner, the skull acts as a low-pass spatial (not temporal filter), but not because of direct electrical effects per se, such as different impedances at different frequencies. In further comparing scalp EEG to cortical ECoG, considerable differences can be observed in ECoG electrodes spaced just millimeters apart, which is not generally the case for scalp-recorded EEG (Cooper et al., 1965).

High-Density Electrode Arrays

Several of the studies discussed above considered synchrony in various frequency bands between electrodes. However, the local domain of synchrony, at least for gamma rhythms, is about 1 cm² (Menon et al., 1996, discussed further below). This is also the approximate size of activation regions typically observed in fMRI studies, or of cytoarchitectonic areas, or of discrete visual areas in primate brain. 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 ‘macroscopic’. 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 discussed above are essentially macroscopic, since the diameter and spacing of the electrodes are such that 1 cm² regions of cortex are sampled only once or twice and many tens of cortical columns are sampled beneath each electrode. Optical imaging with voltage-sensitive dyes is a mesoscopic technique, but cannot readily be done on humans. Thus, mesoscopic imaging of human cortex awaits electrical recordings with more densely spaced ECoG arrays with smaller electrode diameters.

Walter Freeman and Helmuth Petsche pioneered electrocorticography with grids of closely spaced electrodes in animals in the 1970s. Both have argued convincingly for mesoscopic imaging (Petsche, 1982, 1984; Freeman, 2000). Petsche studied penicillin-induced seizure activity in rabbits using a 4x4 grid of electrodes with 0.3 mm diameter and spacings of 1 or 2 mm (Petsche, 1978, 1982). He modeled synchronization as arising from interactions of many elementary generators, which are defined as zones “where exactly the same shape of
potential without any phase shift is found”. These are about 1 mm in diameter and probably correspond to cortical columns. These models of synchronization, as well as his studies of traveling wave phenomena, were pioneering results in the field of neocortical dynamics.

Walter Freeman’s many contributions to the study of mesoscopic cortical dynamics in animal olfactory, auditory, visual, and somesthetic systems cannot be completely covered here. Suffice it to say that his applications of nonlinear dynamical analyses to ECoG time series lend theoretical and empirical support to the importance — if not the primacy — of mesoscopic imaging (Freeman, 2000). In addition to his extensive animal work, he has been involved in two human ECoG studies. In the first (Menon et al., 1996), a standard silastic sheet with 1 cm spacing between electrodes was used to look for domains of spatially correlated gamma activity, as had been previously identified in animals. Negative results were reported, suggesting that domains of locally correlated gamma activity existed on spatial scales smaller than 2 cm². It was concluded that a denser array of electrodes, with spacings no greater than 0.5 mm, would be needed to study patches of local correlation. For the
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. It was concluded that the optimal array would have “an electrode interval of 1.25 mm and an 8x8 spatial window of at least 10 mm.” In sum mesoscopic imaging in humans awaits such an electrode array.

**Methodology**

**Recording**

Electrophysiological recordings conducted within the operating room face several challenges that include: 1.) electromagnetic interference, 2.) a non-silent reference electrode, 3.) far vs. local field potentials, and 4.) the affects 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 which can facilitate the acquisition of relatively noise free data are: 1.) low impedance electrodes, 2.) a differential amplifier with good common mode rejection (at least 100dB), and 3.) proper grounding and shielding.

For an amplifier to perform maximally impedances should be kept at a value less than the 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 the recordings will be contaminated by electromagnetic fields (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). In line with this, it is also important to use electrodes that are composed of the same material; using dissimilar metals can result in DC offsets.

A differential amplifier with an excellent common mode rejection feature (e.g., a typical system on the market has a rejection ratio of 106dB, or a 200000:1 reduction, in
60Hz noise) is beneficial because it allows for the elimination of signals occurring in phase at each of the electrodes. Specifically each electrode with respect to the ground electrode will pick-up signals that are both in and out of phase. Now if this common signal is in phase 60Hz line noise, for example, then, based on the properties of a differential amplifier, the common signal (i.e., noise) will be subtracted out, thereby rendering the recording relatively noise free. Furthermore, common mode rejection eliminates the data distorting that can occur with 60Hz notch filters (i.e., notch filters produce a damped oscillatory response when presented with a transient input) (Cooper, Osselton, and 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 as well as thoroughly shield them. Note that in order to activate a shield it needs to be grounded. If the operating room has a designated ground the shield wire should be connected to that, if not, the shield wire can be attached to the amplifier chassis. The amplifier and any head box cables should, also, be kept as far away from any AC cords or powered devices as possible.
**Non-silent Reference Electrode:** The chapter will primarily consider one recording arrangement (a monopolar arrangement or referential montage): voltage is recorded from an epicortical electrode referenced to an electrode placed some distance away (approximately several centimeters). 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”). 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 reflect neural activity 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. Reference electrodes on the scalp or nose will also include ocular artifact from the corneoretinal 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 rereference offline to that electrode. A predicted model of the original reference can also be created in order to obtain a better understanding of the signal in the original reference. It is important to mention that this method does not eliminate the problems inherent to a non-silent reference due to the fact that with differential amplifiers the original reference electrode is directly recorded from, and therefore its effects have not been completely eliminated. But, it does allow for some reduction in contamination.

Crone et al., (2001) have argued for the use of a common average reference in analyzing ECoG data. The technique involves taking the average potential from all non-artifactual 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. If the activity at the original reference site is to be evaluated, then the sum of all channels should be divided by the number of all channels plus one (Dien, 1998a). Nonetheless, it is important to note that with limited epicortical electrode coverage it
cannot be assumed that the common average reference can be used to 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, and Pernier, 1985; Dien, 1998a). Specifically, since 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, and 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 refer to Dien (1998a).

Far vs. Local Field Potentials: Far-field potentials might arise from distant voltage sources, such as the conreoretinal 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, it is considered to be weak compared to the activity arising directly beneath or in the near vicinity of the recording electrode. Also, 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 recordings. Recordings in animals from the crown of a gyri can show far-field effects from the parts of the gyrus buried within the sulcus (for example, Pellegrini 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 (Soltani and Edwards 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). 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).

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Insert Table 1 Here

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**Data Analysis**

Artifact Rejection: The elimination of artifact from the EEG data set is a crucial step. It does not make sense to conduct elaborate analyses on data wrought with
potential confounds. Generally there are four sources of artifact: 1.) EEG equipment (These artifacts are faults and will not be discussed here. For a review see Cooper, Osselton, and Shaw, 1980); 2.) Electrical noise in the patient’s surrounding; 3.) Electrodes and leads; and 4.) Non-cerebral 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. Solutions for reducing the electrical interference were discussed in the sections titled “Recording.” Nonetheless, the most effective way to remove the remaining electrical noise (e.g., 60Hz line noise) involves conducting offline low and high pass filters aimed at removing the contaminant frequency. A second technique involves presenting the stimuli “at intervals equal to an odd number of half-periods of the line noise, so that with averaging the noise will cancel itself out” (Picton, Lins, and 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. Since the currents needed to measure electrode impedances are very low, these measures can be used 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 where stimulation mapping is involved the current applied to the cortex can cause nearby electrode channels to saturate. Saturation can be prevented online with a gate that pauses the recording or offline 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 when this threshold is exceeded that segment of the data is discarded.

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 skull flap is removed and the brain is exposed, clear pulsations are observed with each heartbeat; this can cause a pulse artifact in the ECoG. 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 suggested by Cooper et al., (1980), 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 corrected for in the data offline. Finally a third involves filtering the data offline 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).

As an aside, as previously mentioned anesthetics may also alter the EEG. These artifacts are more difficult to interpret and reject. A general understanding of the various anesthetics and their effects can facilitate the process (see Table 1). 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.

Event-Related Potentials (ERPs): The most basic method for analyzing ECoG data is to make event-related potentials (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. It should be noted that the ERPs recorded from the cortex are much greater in amplitude than those gathered from the scalp and can sometimes be seen in individual trials.
However, in our own experience, the signal-to-noise for cortically recorded ERPs is still low enough that several tens of trials are needed to obtain a stable waveform in the ERP.

Scalp recorded ERPs provide a non-invasive 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 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, dipole source localization techniques have been employed wherein researchers 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 it can be concluded 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.

Like scalp EEG, intracranial EEG has very high temporal resolution, but unlike scalp EEG, intracranial EEG 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, Marinkovic, and 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 than it can be concluded that the structure in question is a generator of the observed ERP component (see figure 4).

Finally, in interpreting the waveforms one should consider the stimuli used to elicit the ERP, the
properties of the scalp-recorded ERP (i.e., amplitude, latency, distribution) in order to obtain a clear understanding of what the intracranially recorded ERP represents. As a rule of thumb, for scalp recordings at least, 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, and Gaeta, 2001).

*Time Frequency Analysis:* Time frequency analyses allow for the investigation of the event-related spectral perturbations of the brain (e.g., gamma activity or 40Hz). For instance, animal electrophysiological studies have demonstrated that synchronized brain activity in the gamma frequency range may be the correlate to feature binding (Gray, König, Engel, and Singer, 1989). In line with the animal findings, induced gamma activity may correlate with feature binding in humans (Müller et al., 1996). Event-related coherence measures can also be used 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 the chapter by Herrmann in this text), 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) have reported high frequency gamma activity (~80-100Hz) in the auditory cortex during a phoneme discrimination task. In a simple intraoperative mismatch negativity (MMN) task, we also acquired high frequency gamma activity (70-170Hz) to deviant tones, but when we conducted the same task using scalp recorded EEG we did not observe the high frequency activity (70-170Hz). Finally, intracranial recording has also provided information on high frequency “ripples” (100-500Hz) in hippocampal and epileptic human cortex (Staba et al., 2002a; Staba et al., 2002b) and has 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 60Hz is a major recording issue, the amplifier low pass filter (LPF) should be set higher for ECoG than what is typical of scalp recordings.

**Conclusion**

Even though intracranial EEG does provide both excellent temporal and spatial resolution, it is still not without problems. Two major shortcomings of intracranial recordings include: 1.) The technique does not employ healthy normal working brains; rather, it employs specific groups of participants namely those undergoing a neurosurgical procedure; and 2.) 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, imaging techniques, such as functional magnetic resonance imaging (fMRI), provide excellent spatial resolution of the intact brain, even though they do not necessarily provide adequate temporal resolution to determine the sequence of the neural events that occur during a task. As such, neuroimaging techniques can
complement the intracranial findings, by allowing for non-invasive investigations of the entire healthy human brain.

Furthermore, as mentioned earlier the spatial resolution of intracranially recorded ERPs is limited by electrode size and spacing. Hence a high-density electrode array will allow for ‘mesoscopic’ imaging of neocortical dynamics in the awake human. Decades of lesion and imaging studies have revealed a mosaic of interacting cortical modules that specialize in different functions. Intraoperative EEG in conjunction with stimulation mapping can be used to identify such modules. Most importantly the technique offers the unique opportunity to look at the patterns of activity within those 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 interacting regions. The technique may allow for the observation of interareal synchronization (Bressler, 1995; von Stein, Chiang, and König, 2000)
between regions identified as functionally connected in fMRI. 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 (Friston, 1995, 1997). Such studies will undoubtedly lead to new insights concerning neocortical dynamics and information processing.
Footnotes

1. Although these electrodes technically rest on top of the pia mater and some arachnoid, in the literature they are typically referred to as ‘epicortical.’
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<table>
<thead>
<tr>
<th>Agents</th>
<th>EEG Effects</th>
<th>EP Effects</th>
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<tr>
<td>Halogenated Inhalational (e.g., desflurane, enflurane, halothane, isoflurane)</td>
<td>Varies based on agent used (see Sloan, 1998)</td>
<td>Decrease amplitude Increase latency</td>
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<td>Nitrous Oxide</td>
<td>If used alone produces high frequency activity (&gt;30Hz) frontally</td>
<td>Decreases amplitude Increases latency</td>
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<tr>
<td>Barbiturates</td>
<td>Increase beta activity</td>
<td>Decrease amplitude Increase latency</td>
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<tr>
<td>Ketamine</td>
<td>Produces high amplitude theta activity and increase beta activity</td>
<td>Increases amplitude</td>
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<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>
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<tr>
<td>Etomidate</td>
<td></td>
<td>Increases amplitude</td>
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<td>Propofol</td>
<td>Dose-dependent depression</td>
<td>Decreases amplitude, with rapid recovery upon termination</td>
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<td>Muscle Relaxants</td>
<td>No effect</td>
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Data gathered from Sloan (1998).
Figure Captions

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.

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 (figure courtesy of the Journal of Neurosurgery in Ojemann et al., 1989).

3. The figure illustrates electrodes embedded in a silastic strip. The silastic strip can be seen resting beneath the dura on the right temporal lobe (figure adapted from Reid, 1989).

4. Illustration of far-field effects. The waveform depicts a typical response to a deviant auditory tone. The generator is thought to be buried within the Sylvian Fissure. Note the polarity reversal across the fissure (see gray boxes).
5. Averaged somatosensory-evoked responses in two patients under local anesthesia. A monopolar scalp needle and an epidural stainless steel ball electrode were placed over the hand area of the somatosensory cortex. The nasion served as the reference. The patient was fully awake, having received no prior medication except for local anesthesia at pressure points for the head holder and at the site of the scalp incision over the premotor area. The contralateral median nerve was stimulated at the wrist at a frequency of 4 cy/sec with monopolar cathodal squarewave pulses of 0.2 msec duration at stimulus threshold and various increments as shown. The analysis time of 200 averaged response was 125-msec. The stimulus was applied at the arrow. The time base and microvolt calibration are as indicated. Negativity is upward. The records of two different subjects (A and B) are shown to illustrate some of the variability of the responses (figure courtesy of Science in Domino et al., 1964).