EEG Mapping for Surgery of Epilepsy

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Summary: This report describes the objectives, problems, and current techniques associated with using EEG maps in the management of surgery of epilepsy. The purpose of EEG mapping in epilepsy is to precisely identify and characterize epileptogenic zones of the brain. Such zones may be single or multiple, pointlike or diffuse, and may be near or distant from the recording electrodes. The resulting measured electric fields are used to obtain information which, when analyzed in light of all the complementary clinical information, can frequently help to localize and describe the epileptic foci with more precision.

Key words: Epilepsy, Surgery of epilepsy, EEG, Clinical neurophysiology, Brain maps

Objectives of EEG Recording For Epilepsy Surgery

EEG mapping for epilepsy surgery is similar to other EEG mapping techniques in that an electrical contour distribution is used to identify and characterize potential sources in the brain. However, in epilepsy surgery, the goal of the mapping is to precisely identify a zone of epileptogenicity with as much accuracy as possible.

The final objective is to resect the brain identified as epileptogenic as completely as possible, hopefully without lesioning any adjacent normal brain tissue. To achieve this objective, presurgical evaluation of surgical candidates requires (1) absolute certainty that the zone identified as epileptogenic is indeed correct, and (2) precise mapping of the epileptogenic zone with an error margin less than one centimeter. EEG mapping from surface electrodes, however, cannot achieve this degree of certainty or precision. Therefore, in presurgical evaluation of epileptics, EEG mapping is always analyzed together with other complementary clinical information which frequently may provide as good or even better indices of the location and extension of the epileptogenic zone.

For example, in a patient with a spike focus maximum at the 10-20 international system electrode F7, we will interpret the mapping differently depending on the clinical seizure type. In patients with clinical seizures suggesting a temporal origin, we will assume that the epileptogenic zone is in the mesial/anterior temporal region and that we see the anterior pole of a dipole oriented in the anterior-posterior direction. In patients with clinical seizures suggesting a frontal origin we would assume a dipole lying perpendicular to the convexity of the frontal pole. This interpretation is in turn complemented by possible abnormalities detected by neuroimaging and other tests. Only cases in which all or at least most of the information is convergent will be considered as surgical candidates.

In other words, identification of a source from mapping is always based on a number of assumptions. In presurgical evaluation of epileptics, complementary clinical information is used extensively to define better these assumptions and, thereby, to increase the precision of the results ("the definition of the epileptogenic zone"). In addition, in many cases, the clinician realizes that mapping from surface electrodes is too unreliable and too imprecise to make a definite surgical decision. This is the reason why semi-invasive (epidural peg and foramen ovale, Awad 1989) or invasive (subdural and depth, Lüders et al. 1982, 1987; Wyllie et al. 1989) electrodes are used very frequently to confirm and to increase the precision of mapping performed with non-invasive electrodes.

Problems of Using EEG for Identifying Epileptogenicity

For purposes of this discussion, we restrict ourselves to procedures that use epileptiform EEG recordings to produce spatial representations of the abnormal electrical activity of the brain. Epileptiform EEG activity is the most specific indicator of epileptogenicity and, therefore, provides also the most specific information about the location of the epileptogenic zone. Other mapping methods that use nonepileptiform EEG signals such as diffuse slowing, frequency alterations, or evoked potentials, have also been described (Gueguen and Gaches 1986; Miszczak and Achimowicz 1986; Nuwer 1987) as indicators of epileptogenicity. All these methods, however, are non-specific indicators of brain damage which may or may not be associated with epileptogenicity.

Ideally, an EEG map can be interpreted by applying an understanding of the physiological and physical principles that produced it (Gloor 1985). Generally, certain assumptions must be made in order to allow this interpretation to occur. Fundamentally, any given electrical map can be produced by more than one underlying source current distribution. There is a many-to-one problem, in that a complex set of brain potential generators is being represented by a relatively small number of measurements. A very complicated system is thus undersampled, and then smoothed, by the recording and processing procedures. Any inference of the source generators, based on this map, is thus generally based on assumptions that the sources are simple dipoles or sheets, and are only as complex as necessary to explain the observations.

Typically, an EEG map is inspected for localized peaks and simple phase relationships that can be used to identify generator foci. For a minimal, straightforward interpretation to be possible, the following assumptions must be satisfied:

The source is a simple charge distribution near the surface.
The source dipoles are perpendicular to the surface.
The head is a uniform, homogenous volume conductor.
At least one recording electrode is essentially over the source.
The reference is not contained in the active region.

These assumptions are based on the fact that the head is a volume conductor of currents generated by various sources, and that certain conditions must be satisfied if a surface potential map is to accurately reflect the interior electrical activity. Currents in and on the head are related to electrical sources in a conceptually simple way, but are affected by a host of phenomena related to the nonideal conditions which occur in real-world situations. The head is not a uniform, homogenous conducting medium free of defects and irregularities. In addition, the actual biological sources of electrical potential may not be simple combinations of dipoles located conveniently near the surface of the scalp.

It is theoretically possible to calculate expected surface potential distributions for given sources in an ideal volume conductor. It is also theoretically possible to compute the location, magnitude, and orientation of presumed electrical generators based on a surface potential map, if certain assumptions are made. However, the application of this theory to a particular clinical situation depends on many assumptions which are not generally satisfied.

Several key points must be emphasized. The first is that the exact position, distribution, and orientation of the underlying potential generators will have a profound effect on the surface potentials which are measured. The second point is that the presence of both normal and abnormal irregularities in the brain and skull will affect the surface potentials produced by a brain source (Figure 1). This is because the volume-conducted currents will flow preferentially through low-resistance paths, distorting the surface potential distribution. Finally, the choice of reference will affect the form of the EEG measurements. In particular, if the reference is within the potential field of the discharge of interest, it will not generally be possible to calculate a "monotonic" potential field for plotting, unless one pays close attention to the phase relationships between the signals (Figure 2).

Overall, as mentioned above, any EEG result must be interpreted within the context of all the additional clinical information, plus empirical evidence based on previous experience. Although general physiological and physical principles can be used to explain the phenomena involved, clinical interpretation of a particular set of measurements may be based on experience and information that is not easily derivable from first principles.

Effect of Source Dipole Orientation

The fundamental problem in using scalp electrical signals for defining the boundaries of epileptogenic zones arises from the fact that EEG measurements reflect secondary electrical currents in the head, and these may not be simply related to the relevant potential sources. Assuming that an epileptogenic zone can be represented by simple combinations of dipoles, there are various factors which will affect the surface potential distribution, leading to problems of interpretation.

One basic complication can be attributed to the orientation of the source dipole. Although it is often assumed
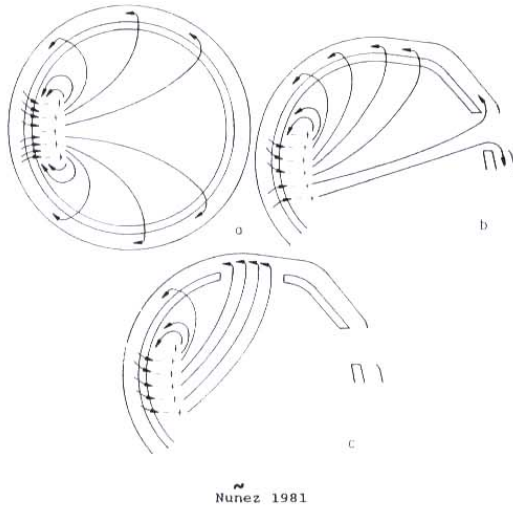
Figure 1. Current flow due to cortical dipole layer in (a) spherical head with no holes, (b) nonspherical head with eye holes in skull, (c) nonspherical head with surgical hole in skull (with permission, from Nuñez 1981, p. 7).
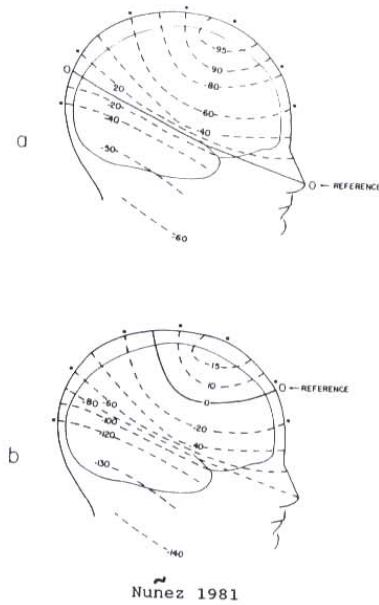

Figure 2. Effect of reference electrode location on the peak-to-peak amplitude of an EEG waveform. In (a) and (b) the same evoked potential distribution indicates different regions of polarity shifts depending on the location of the reference electrode (with permission, from Nuñez 1981, p. 179).

that cortical generators giving rise to scalp EEG potentials are reasonably perpendicular to the scalp surface, this may not be the case. Clearly, when this assumption is correct, one can normally expect the highest amplitude signal to occur at a location directly above the source. However, if the dipole is oblique or parallel to the scalp surface, very different surface potential patterns can result (Lesser et al. 1986; Adelman et al. 1982).

There are a variety of situations which will result in a generator dipole that is not perpendicular to the scalp surface.

Firstly, any generator that lies within a cortical fissure will present a dipole at an angle to the scalp. Nearly 70% of the cortical surface lies within the depths of the sulci (Carpenter, 1972). In addition, certain brain areas contain large amounts of grey matter that curve relative to the skull, producing regions that are not only variously oriented, but have varying distance from surface electrodes. The most notable of these are the mesial frontal, parietal, and occipital cortex, and the basal temporal cortex. Figure 3 illustrates a typical dipole resulting from a mesial temporal lobe focus, as revealed by an invasive electrode array (Lüders et al. 1988).

When a generator dipole is oblique or parallel to the scalp, the resulting surface potentials can show two primary features: phase reversal associated with the dipole center, and false localization of the potential max-

imum. Since both the positive and negative portions of the dipole may be recorded at the scalp surface, the surface potential can exhibit two "maxima" of opposite polarity, associated with each end of the dipole. Furthermore, as a result of volume conduction, these maxima may not lie directly above the generator, but will be disposed laterally as a function of current spreading in the skull and scalp. A map based on such a measurement might be interpreted in a misleading fashion, particularly if the raw waveforms are not available as a standard of reference. Ultimately, a naive interpreter may not only misidentify the location of the source, but the exact nature of the potential generator may be misinterpreted.

Figure 4 illustrates an example of paradoxical localization of parasagittal sharp waves in a patient with epilepsia partialis continua (Adelman et al. 1982). This patient presented with clonic movements of the right thigh, which were associated with sharp waves over the midline and right hemisphere. Whereas previous investigators had attributed this phenomenon to depressed activity in the diseased left cortex, the surface potential is correctly explained by a seizure focus on the mesial surface of the left precentral gyrus within the interhemis-

Voltage distribution in patient with focus
in the mesial temporal region
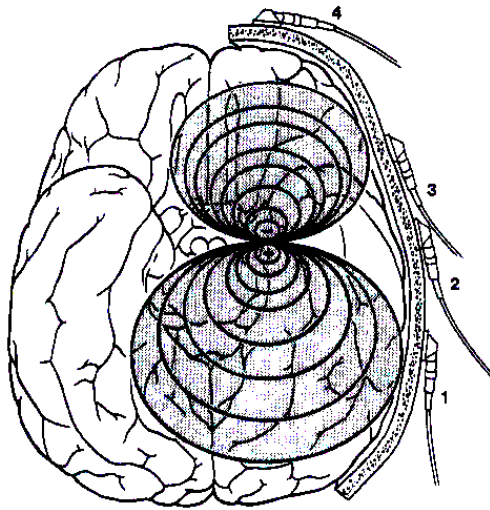
Lüders et. al. 1989

Figure 3. Dipole in patient with focus in the mesial temporal region (with permission, from Lüders et al. 1989).

pheric fissure, producing an oblique dipole. As a result, the largest amplitude sharp waves appeared over the right hemisphere, leading to paradoxical lateralization.

Effect of Source Dipole Location

There are a variety of complications which can arise relative to the location of a dipole in comparison to the recording electrodes. These are most troublesome in the case of deep-seated foci. When foci are superficial, it is generally possible to assess the situation by providing an adequate number of surface electrodes with judicious choice of reference locations. When a focus is deep, however, it may be impossible to gain an adequate "vantage point" with any electrode complement. A deep-seated source can generate a "far-field" potential, which produces only small voltage differences between surface recording electrodes (Figure 5). In essence, it is impossible to find a scalp electrode reference that is not contained in the active region, resulting in a small or zero potential for all electrode pairs. As a result, the source can be estimated only by invasive electrode placements, which are capable of monitoring more limited areas.

Effect of Multiple Source Dipoles

In reality, the potential sources associated with epileptiform sharp waves and seizure patterns are often not
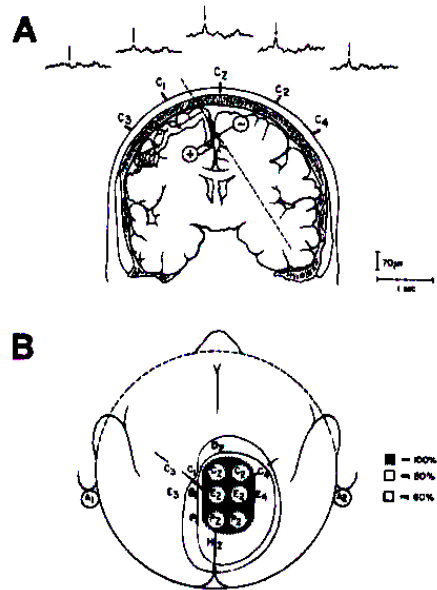

Adelman et. al. 1982

Figure 4. A) Oblique dipole illustrates maximum distribution of the sharp wave over the vertex and right hemisphere from a focus in the left mesial precentral gyrus. B) resulting scalp contour map shows paradoxical lateralization over the contralateral hemisphere (with permission, from Adelman et al. 1982).

simple in nature. A given zone may produce one or more dipoles, each of which produces volume conducted currents. These currents are summated at the site of a recording electrode, producing a single net electrical potential which is measured. Depending on the relative magnitude and sign of each contributing potential, the net measurement may not be a reliable indicator of the electrical situation deep in the brain. In addition, normal potentials arising in the region of the recording electrode will further add to error in defining the potential in question.

Multiple sources can combine to produce various net results. A superficial source can overshadow a deep source, effectively distorting or even hiding it. Since the amplitude of a measured potential is inversely proportional to the square of the distance from the recording electrode, nearby sources can have a significantly higher appearance on recording electrodes.

Even if two sources are at a comparable depth, their combination can lead to a confusing net potential. The resultant of two sources will be the vector sum of their individual dipole moments. This can cause cancellation
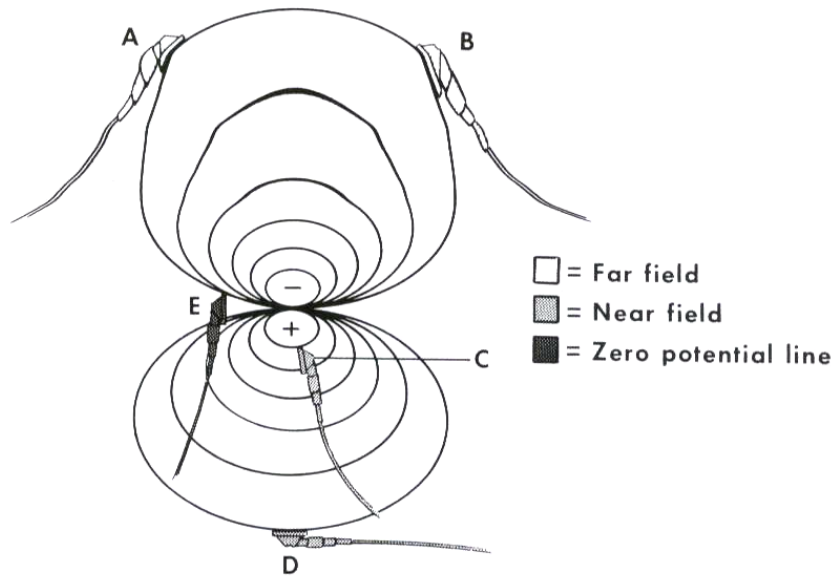
Figure 5. Basic concepts related to near-field and far-field potentials. Electrodes A and B, being relatively distant from the source, record the same potential, despite the fact that they are far apart. Electrodes C and D are separated by the same distance, but will record a much greater potential because C picks up a near-field potential. Electrode E illustrates that even a close electrode can record zero potential in the case of a bipolar generator (with permission, from Lüders et al. 1989b).

at locations that would otherwise provide important localization information. Multiple sources can thus combine to produce a "phantom" source, whose properties may not realistically reflect any of the actual abnormal activity.

In addition to multiple dipole sources, an epileptogenic zone almost always consists of a continuum of dipoles, resulting in a sheet dipole. Such a source may cover an extended region of brain, with the constituent areas lying at various depths and orientations. Again, both reinforcement and cancellation are possible relative to each recording electrode, producing a variety of surface potential situations. The net surface potential is proportional to the solid angle subtended by the recording electrode; unless a sheet is parallel to the surface, the maximum surface potential may be at a location other than directly over the affected area (Figure 6).

In the same way that two dipoles can cancel each other relative to a distant electrode, a dipole sheet can produce an effectively "closed" field, whose potential contributions will be negligible to a wide range of surface recording sites (Figure 7). This is particularly likely in the basal/mesial areas of the temporal cortex, and the hippocampus, where cortical enfolding is so prevalent. The amygdaloid nucleus, with its complex connections, fibers, and subnuclei, presents an even less regular struc-

ture for the orientation of electrical dipoles. Unfortunately, these very areas are among the more common locations for epileptogenic foci to exist (Gloor et al. 1963).

Effect of Irregularities in the Volume Conductor

When interpreting the potential distribution provided by a scalp EEG map, it is often assumed that there is a direct relationship between a surface peak and a cortical source lying below the electrode(s). If cortical generators were in fact relatively superficial, this would be reasonable only if the head were a uniform, regular volume conductor with no appreciable discontinuities. However, a number of conditions exist which limit the validity of this assumption.

The head consists of a series of roughly concentric layers which separate the brain from the surface of the scalp. These layers consist of CSF, meninges, bone, and skin, each of which presents different electrical characteristics to the currents which conduct the EEG to the surface. As a result of these layers, there is a considerable amount of current spreading, which causes the potential from localized foci to appear in a much broader area of the scalp (Nünez 1981; Neshige et al. 1988). Foci of limited extent, below about 6 square centimeters, under-
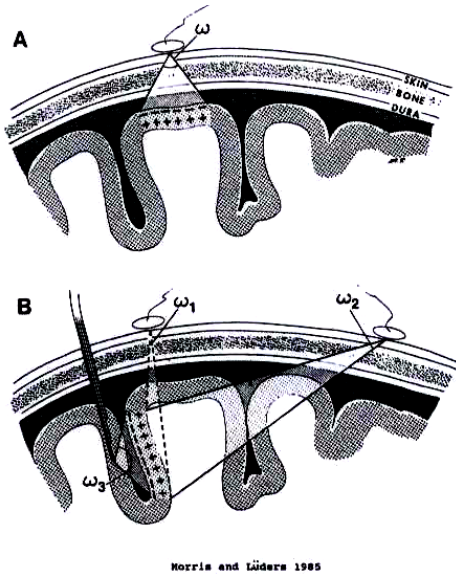
Figure 6. A) Scalp electrode over a gyrus can easily detect potential changes because solid angle is large. B) Scalp electrodes do not detect potential because solid angles are relatively small. A depth electrode, however, detects the potential (with permission, from Morris and Lüders 1985).
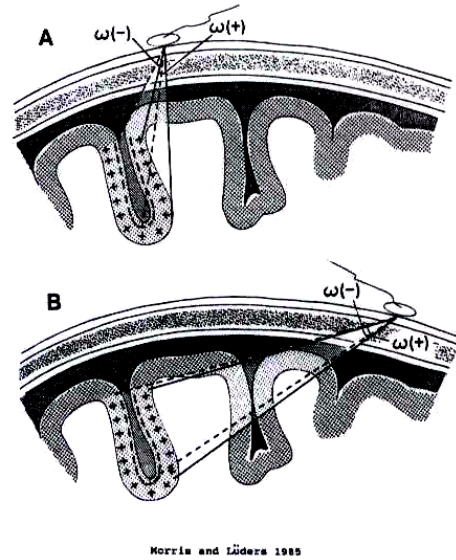
Figure 7. Both banks of a fissure are generators and the potentials 'cancel' each other when measured by scalp electrodes (with permission, from Morris and Lüders 1985).

go sufficient spreading as to render them essentially undetectable with surface electrodes (Figure 8).

Spreading in itself would not be an insurmountable problem, since it is theoretically possible to recover deep dipole sources based on observed surface potentials, using appropriate mathematical transformations. However, such recovery is guaranteed only in the ideal of a perfectly spherical, concentric conductor, upon which we can place electrodes in any desired location. Clearly, the head does not present a perfect globe, and we are severely limited from placing electrodes on, for example, the face or neck, which may be the preferred vantage points for certain sources. In addition, the head is also irregular in that it contains openings which may be normal or abnormal, presenting low-resistance paths to conducted currents. The resistivity of scalp or brain tissue is as much as 80 times smaller than that of bone. As a result, surface potentials in the vicinity of these openings will be unusually high, and may suggest the presence of sources which are in fact far from generators.

Effect of Automated Mapping Algorithms

With adequate care, it should be possible to construct an unambiguous map of the scalp topography of a given epileptiform event. Such determinations may be influenced by prior assumptions, such as whether or not the source actually contains a dipole which is "visible" to the recording electrodes. Overall, the complementary clinical information and experience dictates the interpretation of a particular map, above and beyond theoretical considerations which may be generally true, but not relevant to the specific case at hand.

When commercial EEG mapping systems are applied, there is considerable risk of losing accuracy due to the "enhancement" algorithms applied to the data. Many topographic mapping systems employ reference correction, electrode interpolation, or other processing routines, to provide a more visually "appropriate" map. However, when the goal is to precisely localize a particular focus which may appear on only one or two electrodes, these algorithms can considerably degrade the essential information.

Similar concern should be given to systems that apply "source recovery" or "source derivation" algorithms in an effort to reduce the "blurring" due to current spreading in the skull and scalp. While these approaches may be theoretically sound and offer good results in certain cases, they are not generally applicable in a risk-free fashion. For example, source derivations (Rodin and Cornellier 1988) can effectively sharpen images of focal generators that lie near the surface, when appropriate

A Reference = A1 + A2

Fp1 Fpz Fp2
F3 Fz F4
F7 F8
C3 Cz C4
T3 C1 C2 T4
P3 Pz P4
T5 T6
EOG O1 O2 EMG

B Reference = A1 + A2   Cortical stimulation

A(1) — (–)
B(1) — (–)
C(1) — M: fingers (I,II,III)
D(1) — M: fingers (II,III)
E(1) — S: finger (I)
F(1) — S: palm
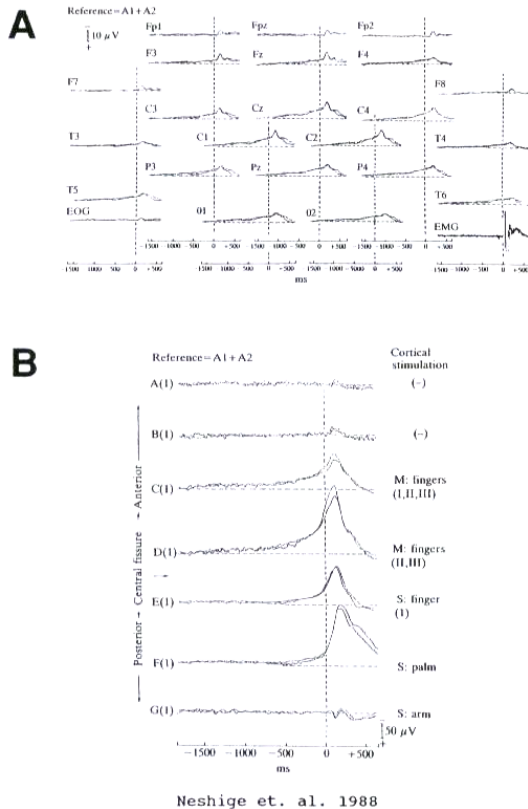G(1) — S: arm

Neshige et. al. 1988

Figure 8. A) Normal scalp-recorded waveforms of movement-related potentials in a 38-yr-old man. B) Potentials recorded invasively from subdural electrodes placed in front of and behind the left central fissure (1 cm spacing). The scalp recordings suggest a widespread potential over the central and parietal regions. However, the subdural recordings demonstrate a clear maximum near the central fissure (D1), with rapid "falloff" in adjacent electrodes. (With permission, from Neshige et al. 1988).

electrode arrays are used. However, such corrections can introduce errors when more than one active site is present or when an active site is near the edge of the array. Thus, such techniques can only be used with confidence when certain localization information is already available, and therefore, should only be used by investigators who have a clear understanding of the assumptions underlying this methodology.

In general, enhanced mapping techniques should be made available for informed use in particular circumstances. However, in the same way that experience dictates the interpretation of raw EEG's and simple maps,

experience will be required in order to develop sound and consistent guidelines for the use of these methods. It should be generally remembered that the precision of the final result is only as good as that of the raw data, and there may not be enough detailed localization information in the scalp EEG to justify choosing one enhanced map over another.

Defining the Epileptogenic Zone(s)

A variety of EEG attributes are used to define epileptogenic zones, which relate to either ictal or interictal activity. Within this broad classification, there are a range of measurements that can be taken to reflect the degree of epileptogenicity.

Interictal activity

Interictally, clinicians look for outstanding sharp-wave activity that can be interpreted as epileptiform. However, there is no precise, universal definition of what constitutes an interictal sharp wave, so there is room for interpretation by individual clinicians. Accurate identification of sharp waves is a complex process that is taught semi-empirically to clinical electrophysiologists. The normal EEG contains many sharp transients and waveforms that are non-epileptogenic or even artifactual in nature and, therefore, could be very misleading if confused with epileptogenic activity (Klass and Westmoreland, 1985). Extended formal training is essential for reliable identification of epileptogenic transients. In other words, the primary and essential condition for accurate definition of an epileptogenic zone by mapping is correct identification of epileptogenic vs. non-epileptogenic interictal (or ictal) activity.

Given that a particular entity is considered epileptiform, this opens the question of precisely how to quantify and map the object. In any event, it is currently impossible to implement a completely automated system for mapping interictal epileptiform transients.

Given that a particular sharp wave is considered epileptiform, it must be reduced to a quantity in order to be mapped. Despite the availability of a variety of methods (peak-to-peak, total energy, composite parameters), metrics based upon amplitude are the only values that can be readily captured and communicated unambiguously. These will be discussed in the section on mapping techniques.

The exact part of a sharp wave that is measured can affect the outcome of a map. When absolute amplitude of spikes are mapped, early components show a more localized field than later components (Takahashi et al.

1985; Thickbroom et al. 1986). It can also be observed that the slow afterdischarge of a spike-wave complex has a broader distribution than the initial sharp wave. It would appear that the early components of interictal sharp waves are the most likely indicators of localized epileptogenicity, but this has not been specifically proved.

As described previously, the distribution calculated for a given sharp wave may depend on whether or not a "visible" dipole is assumed to exist. Thus, a given EEG event can give rise to more than one set of parameterizations, depending on the assumptions. When a dipole is thought to exist, attention must be paid to the phase and polarity as well as the magnitude of each channel. While automated techniques can assist in this procedure, there is currently no substitute for the careful scrutiny of an experienced electroencephalographer, in the quantification of each spike.

Wade and Ebersole (1990) mapped individual spikes and reported consistent differences in surface maps produced by mesial temporal foci when compared to non-mesial or extratemporal foci. In particular, mesial foci produced the appearance of a stable lateral dipole, whereas the other foci did not. It is not entirely clear, however, what the "meaning" of the maps is, other than to separate two broad types of foci. Such surface potential maps can thus have value in classifying abnormalities, in the context of a given set of clinical problems.

It is often found that interictal sharp waves do not conform to a simple model of isolated, localized events. Spikes may occur in a repetitive fashion, in which succesive bursts have a different distribution from the initial discharge. It is logical to define the initial focus as the location of greatest epileptogenicity, but it is not clear whether secondarily involved areas should be considered epileptogenic and mapped, as well.

The field of a particular spike may be very localized. However, as large numbers of spikes from a given patient are studied over a period of time, a broader distribution can result (Figures 9, 10). It is reasonable to expect that a better clinical picture can be gained by studying the distribution of a number of spikes over time. Among the candidate metrics for mapping are spike counts, spike frequency (count per unit time), and peak spike frequency. It may also be observed that such "hot spots" can move over time in a particular patient, suggesting slow changes in particular areas' epileptogenicity. This is another subject that would benefit from objective study.

Seizure activity

The locus of seizure onset is usually located within and, in general, is relatively more restricted than the epileptogenic zone mapped by analyzing the distribution of the interictal epileptiform activity. It is generally assumed that the locus of seizure onset represents the zone of lowest seizure threshold within the "interictal" epileptogenic zone. The identification of a seizure onset requires at least the same special training described above for the identification of interictal epileptogenic activity. In other words, the mapping of ictal onset will be reliable only if the identification of the ictal onset was done by an experienced electroencephalographer. Automation of this process is currently impossible.

Generally, seizure onset may be identified with the first occurrence of 1) sharp waves, 2) rhythmical activity (often in the theta range), 3) paroxysmal fast waves, or 4) an electrodecremental pattern. A seizure is almost invariably produced by spreading of the epileptogenic process to invade the adjacent areas of the brain including, very frequently, normal brain. In many cases, secondary generalization with involvement of the "whole" brain can be seen. Therefore, in general, only the onset of a seizure is an index of high epileptogenicity. Later areas are of considerably less importance for identification of the area of maximum epileptogenicity.

The spreading pathway of a seizure may be difficult to comprehend because a great deal of information must be absorbed visually. A "motion picture" display yields data that may be too large to comprehend. However, single frames may provide such limited information that generalized conclusions may be spurious (Rodin and Ancheta 1987).

Advantages and Limitations of Recording Methods

For mapping of EEG in presurgical candidates, we use different methods ranging from non-invasive scalp electrodes to highly invasive depth electrodes. The sensitivity of a technique is usually a function of its invasiveness, but this does not necessarily mean that the invasive technique is always advantageous.

Scalp electrodes

Scalp recordings are relatively insensitive, for the reasons described above; nevertheless, they provide a good overview of the general situation, and give essential information to decide on which invasive recordings to use. Closely spaced electrodes can be used very effectively in most cases to refine localization derived from standard montages. Often, maximal amplitude sharp waves can be found at locations other than standard (e.g. 10/20) locations (Morris et al. 1986). In addition, certain distributions of epileptogenic activity seen on the scalp form topographic signatures which have, by experience, been

EPILEPTOGENIC AREA

MULTIPLE INDEPENDENT SPIKE FOCI
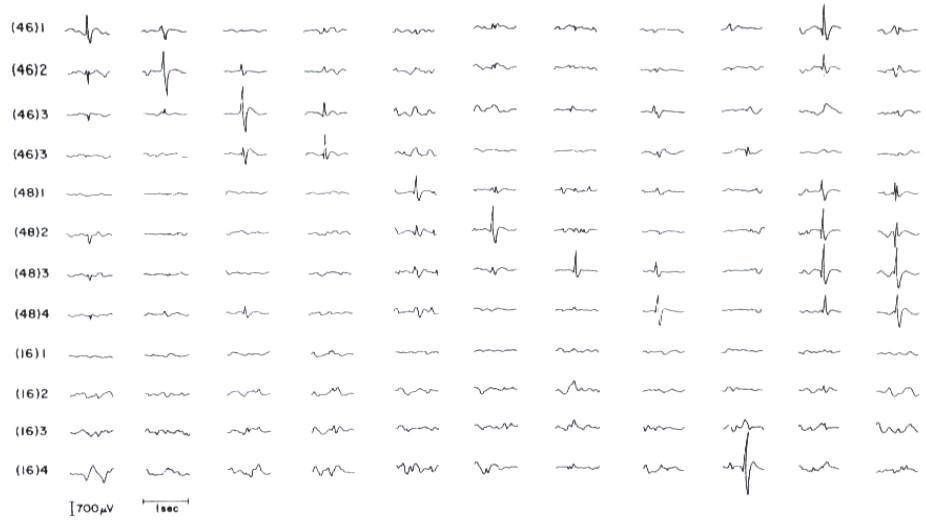
Lüders et. al. 1984

Figure 9. Recordings made via electrocorticography of the temporal pole revealing multiple independent spike foci (with permission from Lüders et al. 1984).
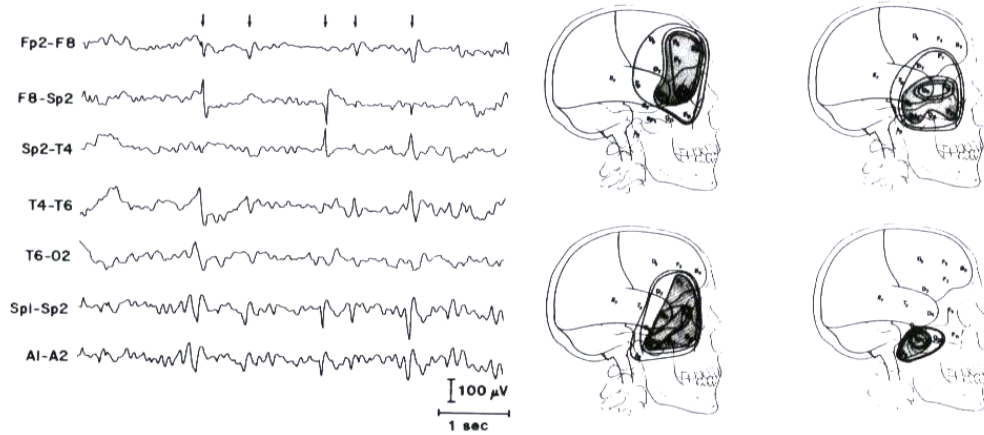
Lüders et. al. 1989

Figure 10. Variable scalp spike distribution in a 37-yr-old man with complex partial seizures since the age of 9 (measles encephalitis) (with permission, from Lüders et al. 1989a).

associated with particular electroclinical locations.

Scalp recordings may be severely limited in their ability to detect foci in certain cases, particularly if the main focus is obscured due to distance from the recording electrodes. The previously described source and conduction phenomena play a role in complicating their interpretation. It should be generally noted that epilepsy surgery candidates can provide a particularly "hostile" EEG environment due to increased occurrence of confounding factors such as abnormal background activity, traumatic or surgical skull lesions, and muscle artifact accompanying the important discharges such as ictal onset.

In cases where the epileptiform activity appears at the scalp in a distorted or spread fashion, it is particularly difficult to ensure that the reference is not included in the active area. It not infrequently becomes necessary to compare a given sharp wave as measured with two or more montages, in order to determine the "true" distribution (Lesser et al. 1985). Apparently discrepant results can be obtained by substituting reference electrodes or by using transverse vs. longitudinal montages. Here, it may not be safe to assume that a given discharge is exactly zero at distant electrodes, or that background EEG activity is negligible at the instant of the discharge.

Sphenoidal electrodes can provide a valuable adjunct to surface placements, when a mesio-temporal epileptogenic focus is suspected (Morris et al. 1989). When a unilateral sphenoidal/anterotemporal interictal focus is observed, there is a high concordance with a mesiobasal/anterotemporal location as identified by invasive subdural electrode arrays.

Invasive electrodes

Invasive recordings, by measuring the electrical field from a shorter distance, are significantly more sensitive. However, they provide a more limited view, concentrating the attention of the observer to the immediate area covered by the electrodes. Placements such as basal temporal and limbic locations are often probed very sparingly, to minimize adverse effects of the electrodes. Such placements thus cover a very restricted area. In addition, the fields measured by invasive electrodes are very localized; it may not be correct to consider these measurements as adequately sampling of a continuous field which can be mapped.

Invasive recordings fall into two broad categories: enhanced surface recordings, and true depth recordings. The choice of recording method is dictated by the particular clinical setting and a detailed neurophysiological picture gained by a detailed evaluation with non-invasive electrodes. There is no routine way to specify the electrode placements which will be required in order to localize epileptogenic areas.

Enhanced surface recordings can be obtained with epidural pegs, foramen ovale, or subdural grid electrodes. These effectively sample a smaller region of the cortical surface, plus avoid artifacts due to muscle, eye, and electrode motion. Since a much smaller brain area is sampled, there are spacing issues associated with choosing the exact placement. The investigator must take care to ensure that the electrodes will in fact sample the suspected focus, since it is much easier for even a nearby focus to be relatively silent to these electrodes.

True depth recordings are obtained by inserting electrodes directly into the brain. These electrodes are capable of monitoring deep areas, particularly the hippocampus and amygdala. The sampled field is even smaller than for "enhanced surface electrodes", giving these electrodes a "hit or miss" character if epileptogenic foci are extremely localized. These electrodes are particularly useful in monitoring the onset of seizures whose origin is in the mesial temporal regions, and for which clinical information and precise surface recordings point to a hippocampal seizure origin, but without definite lateralization information.

Mapping Techniques Used for Surgery of Epilepsy

It should be emphasized that in a clinical setting, epileptogenic foci are best identified by the convergence of results from various independent tests. Mapping techniques are useful only in the context of an overall diagnostic program, that considers the relative value of different sources of information (Engel 1987). In evaluating hundreds of patients for epilepsy surgery, we have found a relatively small percentage that conform to a "standard" clinical picture, and whose EEG abnormalities might be adequately handled by routine techniques. As a result, virtually all EEG mapping is handled on a case-by-case basis, with close attention paid to the clinical situation, as well as the raw EEG waveforms.

Amplitude p-p at a time

The distribution of a particular sharp wave can be mapped once it is reduced to a metric. While there are a variety of methods for doing so, for the reasons mentioned above, the only reliable method is to use a technique in which an experienced electroencephalographer or EEG technologist precisely identifies the component to be mapped. This procedure is necessary for two reasons: one, to screen and accept the event as a bona fide epileptiform sharp wave, and secondly, to ensure that the

spike is properly "captured" by a suitable amplitude measurement.

Ideally, one might choose the amplitude from baseline to the first negative peak as representing the first manifestation of abnormal activity. However, the uncertainty in determining baseline voltage may render this measurement difficult. Therefore, it may be more reliable to take the peak-to-peak measurement from the negative peak to either the preceding or following positive peak. Alternatively, an effective baseline can be computed from the preceding 1 or 2 seconds of EEG. In any case, visual inspection of the waveform is essential for each map.

While such a measurement may seem well-defined, it may be confounded if the various channels are not exactly synchronized. A given spike may exhibit peak voltages at slightly different times on each channel. In such cases, it may be logical to measure each channel at its respective peaks, whether or not these samples coincide. In this case, a semi-automated technique can be of great value, given that the investigator can adequately define a "window" of acceptance, within which the computer can find appropriate waveform maxima and minima.

In our laboratory, for example, we often map a spike by taking a selected peak to peak measurement, and indicating on a map the distribution of electrodes which contain 90%, 80%, and 70% of the maximal value for that peak. This does not produce a topographic contour map per se, but serves to identify the important sites in a well defined fashion. Through continued experience with such maps, our clinicians learn what to expect in a range of situations, for example, we know how a mesial temporal focus will distribute on the various scalp, sphenoidal, and invasive electrodes. We are thus moving in a stepwise fashion from an understandable, manually generated map, to a more computer assisted one (Collura and Vuong 1989; Mohansingh and Collura 1989; Vuong et al. 1989).

Frequency of spike occurrence

In a clinical setting, an electroencephalographer may evaluate hundreds or even thousands of spikes, to create an overall picture of the neurophysiological abnormalities. Generally, spikes are gathered into groups according to type and location, and several example spikes mapped to illustrate the distribution. However, a different distribution may result if all such spikes are mapped, providing a more accurate view of the abnormal activity over an extended time. Such a view is neither a snapshot nor a movie, but rather a summary.

Spike frequency counts are particularly well suited to recordings made with subdural electrode arrays. Such electrodes provide a large number of recording sites on the cortical surface. However, the area surveyed by each electrode is quite limited, and the cortical potential field is consequently undersampled. To create a potential gradient map from such recordings would be questionable, given this undersampling. Therefore, it is more meaningful for the clinician to know how many abnormal sharp waves are observed on each electrode over a period of time. Such counts can be represented in a summary map which groups electrodes that have similar counts. Despite the fact that such a map is not a true contour, it does provide precise localization information, and may have considerable value in the planning of a resection.

Seizure evolution

The location of seizure onset, as indicated above, most probably represents the region of highest epileptogenicity. This requires, of course, that the precise area of onset be visible to one or more recording electrodes. While this may seem obvious, it is not always possible to ensure that such an electrode is available. Surface electrodes provide a broad survey of the brain, but deep foci may be silent, and even superficial foci may be paradoxically localized. In addition, surface recordings are often contaminated with muscle and eye artifact, particularly during the moment that a seizure begins.

Depth electrodes provide a means for probing areas hidden to surface placements; however, it is not always possible to ensure that a depth electrode will be located adequately near the seizure focus. A spatial sampling problem results from the smaller measured field discussed earlier. It is not generally possible to monitor all suspected brain areas, even when multicontact depth electrodes or grid arrays are used. This has practical importance in the interpretation of maps which appear to reveal a seizure "onset".

When a well-defined "onset" is visible in the EEG, it is possible to map a distribution of the amplitude of the initial seizure pattern. While this provides an overview of the size of the EEG signal associated with the seizure at an instant, it does not necessarily reflect the "real seizure onset". In other words, if invasive electrodes are misplaced or if surface electrodes are too insensitive to pick up the "real seizure onset", the recordings will identify spreading as "onset" and can easily mislead the observer (Figure 11). As mentioned already above, more important than a beautiful map is the correct interpretation of the "seizure onset," taking into account all the pertinent clinical and neurophysiological information.

Techniques are available for estimating the pattern of seizure propagation independent of the signal amplitude. Gotman (Gotman 1986) has applied EEG cross-spectra to the calculation of propagation times be-
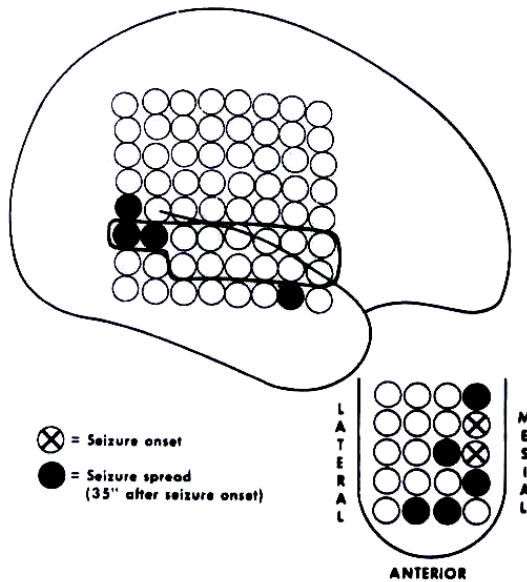
Lüders et. al. 1987

Figure 11. Seizure spread as revealed by subdural electrodes. Onset of seizure at the mesial temporal region spreads 35 sec. later to the temporal convexity, where it involves selected electrodes. Thus, the "onset" as revealed by lateral electrodes is actually an expression of a seizure pattern that had spread into the lateral convexity (with permission, from Lüders et al. 1987).

tween channels. However, this technique depends on the assumption that the seizure propagates in a "linear" fashion, much like a traveling wave in a conducting medium. Since the propagation of neuronal signals in the brain is not a simple wave phenomenon, interpretation of crosscorrelation results may not be straightforward in this application. Additional techniques based on power spectra, coherence, and "mutual information" have also been applied to seizure propagation (Lopes da Silva 1987). These can overcome the assumptions of linearity and provide improved estimates of time delays between EEG signals. However, due to the complexity of the underlying generating and active propagating mechanisms, it is not always possible to pinpoint a definite seizure "source" with confidence.

Conclusion

EEG mapping is an important tool in the presurgical evaluation of epileptic patients. It can be used to identify and characterize epileptogenic foci, and provides a valuable adjunct to conventional EEG.

Overall, there does not currently appear to be a generally reliable mechanical, mathematical way to generate useful maps for surgery of epilepsy. Clinical practice is necessarily dominated by the need to combine a range of diagnostic information into an overall picture of the abnormal process, and to interpret specific results in this context. EEG maps do not follow a simple, prescribed relationship to epileptogenic foci, and it is not likely that a simple algorithm can be developed to reveal foci. Given the importance of this contextual framework, we cannot consider all EEG maps in the same way. The interpretation of a given map is not an isolated procedure, but must be based on assumptions suggested by other clinical information. The map then provides an opportunity to either confirm or modify a visual clinical gestalt, which is focused on identifying the location and nature of one or more abnormal neural generators, and their effect on the patient's life.

Given this perspective, the refinement of sophisticated EEG mapping systems takes on secondary importance to the development of integrated systems. The significant opportunities for progress appear to be in the integration of neurophysiological data with imaging information from other sources, such as MRI, MEG, and other techniques.

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