HANDBOOK OF ELECTROENCEPHALOGRAPHY AND CLINICAL NEUROPHYSIOLOGY

EDITOR-IN-CHIEF A. REMOND

VOLUME 5

Evaluation of Bioelectrical Data from Brain, Nerve and Muscle, II

EDITORS: M. A. B. BRAZIER AND D. O. WALTER

Brain Research Institute, University of California, Los Angeles, Calif. (U.S.A.)

PART B

EEG Topography

EDITOR: H. PETSCHE

Neurological Institute of the University and
Brain Research Institute of the Austrian Academy of Sciences, Vienna (Austria)

ELSEVIER

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Preface

The title of this Part of the Handbook may not give a sufficient indication of the nature of its contents. Since the earliest days of electroencephalography it was recognized that important information may be present in the spatial distribution of the recorded signals. As well as similarities, certain differences were observed in the simultaneous two-channel records made by Berger, and he used this observation as evidence in support of his thesis that the source of EEG waves is within the brain. The electrical activity of the brain is generated in a three-dimensional medium. Information is lost in the conventional EEG because the activity is only sampled at discrete points, usually on a surface, and because the tissues which are not electrically active produce spatial averaging and decreased resolution. This Part of the Handbook attempts to gather together all those methods which aim to recover some of this lost information by examining the relationship between the EEG and the two-dimensional fields on the cortical surface or the three-dimensional field within the brain mass. This approach seems an essential prerequisite for relating EEG activity to brain function.

As well as drawing attention to interesting techniques (even if sometimes representing no more than desperate efforts) we hope that our accompanying remarks will help to increase insight into EEG generation so that some of the pitfalls of interpretation may be avoided.

The methods have been grouped into a few main classes. As well as describing their aims and techniques, these classes have sections dealing with results obtained in man and in animals. This may help in surveying the contents and making the book more useful for reference purposes. However, it seemed necessary to give more emphasis to results. This is because several of the methods quoted were only ephemeral and did not lead to results which furthered the understanding of brain function. Nevertheless, these are included to help young scientists steer a course avoiding those perilous rocks on which others had foundered.

It was not possible to avoid including some mathematical techniques which may also be described in other Parts of the Handbook. These methods are being applied more and more to our field. Their presentation in a different context may aid the reader's understanding of them and prompt intellectual stimuli of a kind different from the ones these methods were originally intended to serve.

We have attempted to interpret the work of many scientists. If we have interpreted incorrectly, without due emphasis, or erred by omission, we can only apologize and reiterate our conviction that any method attempting to look at EEG topography, whether in two or three dimensions, may further our understanding of the human brain.

March 1972

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Section I. Introduction

Many Parts of this Handbook consider the problem of analysing and interpreting the pattern of electrical activity represented by each individual channel of EEG signal. In discussing the problems of clinical and neurophysiological interpretation, the importance of relating events occurring simultaneously over many channels has also been stressed. This Part is concerned with special methods which take account of events occurring in all the channels of a multi-channel record to aid interpretation, and to derive meaningful information about the distribution of electrical activity at all points in the brain and surrounding tissues and its variation with time. These methods are usually called *topographic* because they are used to determine the distribution or topography of activity over the surface of the skull and in the volume of the brain.

The term "EEG" is used in many ways by different workers. It is used to describe the graphs of the final record, the techniques of recording, the apparatus that is used, or the electrical activity of the brain as a whole. In this Part "EEG" refers to the records of the electrical activity of the brain.

A. THE AIMS OF TOPOGRAPHIC METHODS

It has been known since the time of Berger that the electrical activity recorded from outside the brain is generated in the grey matter of the cortex. For this reason, a full description of it requires at least a five-dimensional system. Two dimensions (X and Y) are required to identify each point on the skull, one (Z) for indicating the depth of the grey matter, one for the electrical parameter (current density, potential, impedance, etc.) and a fifth one for time. Of course if more than one electrical parameter is included then additional dimensions are also necessary. Moreover, the above set of dimensions assumes that the surface on which the electrical activity is measured is a plane surface or a projection on a plane of the curvature of the skull and brain. In order to identify position with respect to a fixed coordinate system, the Z dimension would also be used to identify points on the surface. If more than one electrical parameter is included then additional dimensions are necessary.

The commonly used EEG techniques only give a limited representation of this multi-dimensional picture that is required for a complete description of the electrical activity of the brain. In any case the usefulness of such a picture, if it were available, would be limited in two ways: firstly by the technical complexity and cost of the apparatus that would be required and secondly by the limited capacity of the human observer to interpret the large quantity of information that would result. For these reasons it is always necessary to limit the information that is to be obtained and this requires a very careful decision about what information is to be discarded and what is required for answering the questions being asked. Whatever transformation and data reduction is made, the electroencephalographer has to use his skill and imagination to interpret this limited information.

The following paragraphs will briefly consider the above dimensions separately:

1. The X and Y coordinates. Conventional EEG methods only sample the electrical activity on the surface of the skull at discrete points because there is a limitation to the number of electrodes and the spacing between them. One aim of topographical methods is to interpolate this sampled activity so that a picture of the continuous electrical surface over the skull can be built up. The fact that the skull is a curved surface, not a plane, was referred to above and this must be taken into account.

2. The Z axis. This is the least accessible parameter in studying the electrical brain activity. Studies along the depth of the grey matter can only be made in animal experiments and during surgical intervention in humans. Even then, the studies have to be restricted to relatively few recording sites and depths. Later discussions of the findings from laminar analysis will show how important it is to obtain more knowledge about the deep processes within the cortex.

3. The electrical parameter. The electrical processes accompanying physiological events are basically the movement and exchange of ions. Ideally one would therefore measure current density. However, the currents produced by neuronal membranes are very weak—of the order of 10^{-12} A at the most. They can therefore only be measured indirectly via the potential differences that they produce in the tissue impedances. This is complicated by the fact that tissue impedance itself may change, but very little is known about this phenomenon at present. Another aim of topographical methods is to make some inferences about the current fields by suitably transforming the measured potential differences.

4. Time. This fifth parameter is the only one that can be represented continuously in the 5-dimensional coordinate system that is needed for the description of the electrical activity of the brain. It will be seen that many methods of topographic analysis also sample activity in the time dimension. This is done for the reasons of technical and information economy referred to above.

In summary we can say that the methods of topography aim to make it easier to find relationships between those parameters which are not explicitly displayed on the conventional voltage/time EEG. The situation may be represented by a pentagon, the five points of which represent the five parameters considered, *i.e.*, X, Y, Z, potential and time, as shown in Fig. 1. It can be seen that information can only be derived continuously in the potential/time plane. This is why the conventional EEG is confined to a presentation of a one-dimensional potential/time record, the X and Y parameters being partly represented, the Z parameter not at all.

When it is considered from this point of view, we see that the discontinuous information about the three spatial dimensions limits our knowledge of the continuum of bioelectric activity. *Topographic methods* may be defined as *those methods which aim to derive information about these parameters which smooths out the discontinuities by using interpolation methods.*

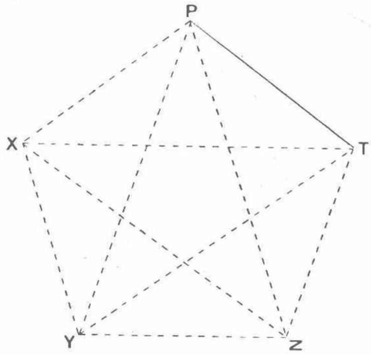

Fig. 1. A full description of the bioelectric activity requires a five-dimensional system of parameters: (X) and (Y) to identify each point on the skull, (Z) for the depth of the cortex, (P) for the electrical parameter and (T) for time. Information can be derived continuously in the potential/time plane (conventional EEG), but in the other planes, information can only be obtained discontinuously (dotted lines). Topographic methods aim to infer this missing information by using methods of transformation and interpolation.

A complete representation of all five parameters in the form of a written record is not possible because at the most, only three dimensions can be represented on a two-dimensional sheet of recording paper. Therefore to obtain the maximum possible information, simultaneous use of topographic and conventional EEG methods is recommended.

This introduction will be completed with a brief survey of current hypotheses and facts about the origin of bioelectric activity and ways of describing its generators. This will be followed by a description of the various methods of topographic analysis from the methodological point of view together with sections devoted to the results obtained by the use of such methods in humans and animals.

Two difficulties arise in giving an account of results. Firstly, many authors have given detailed descriptions of their analysis technique, but have not gone on to publish the results of its application. One must assume that either the development of the technique has been an end in itself for them, or its application has not proved so fruitful as anticipated, or its application has become so routine that it has not been thought necessary to publish the results. The other difficulty is that many of the published results of application of these techniques have been anecdotal rather than scientific. This may be either because no extensive application experiments were carried out, or for a variety of reasons as before. It does not necessarily mean that the method did not prove useful in practice. However, it does make it more difficult to assess the practical significance of the various methods.

B. THE ORIGIN OF THE ELECTRICAL ACTIVITY OF THE BRAIN

Given a potential distribution on a surface enclosing a volume, there is an infinite number of electrical source configurations which could give rise to the distribution. The interpretation of EEG topography therefore requires knowledge of those source configurations which are physiologically viable. The studies referred to below go some way towards aiding this interpretation.

The bioelectric activity of the brain is generated by the grey matter of the cortex and is influenced by the large masses of grey matter in the depths of the brain (Creutzfeldt *et al.* 1966; Brumlik *et al.* 1966, 1967; Andersen and Andersson 1968; Purpura 1969). Studies using laminar analysis of the cortex in animals have made it clear that the voltage changes recorded from the surface of the brain are generated by the cortex itself and are not projected by volume conduction from the thalamic nuclei to the brain surface (Bremer 1949; Bishop and Clare 1952; Cooper *et al.* 1965). The cortical origin of activity was further proved by the findings of a phase reversal in activities recorded from above and below the cortex (Li *et al.* 1956; Green and Petsche 1961; Gloor *et al.* 1963; Calvet *et al.* 1964; Fourment *et al.* 1965; Schneider and Gerin 1970). The role of the thalamus as a moderator and perhaps also initiator of cortical activity (Andersen and Andersson 1968) is treated extensively in another part of this Handbook. However, isolated cortex is able to produce self-sustained rhythmic activity when stimulated (Kristiansen and Courtois 1949; Wright *et al.* 1954; Burns 1958; Echlin 1959; Hirsch *et al.* 1966; Khananashvili *et al.* 1969) and this also occurs in complete hemispheres isolated from the thalamus by separation of the internal capsule and the corpus callosum (Berlucchi 1966; Petsche and Šterc 1968). There is no agreement about the presence of spontaneous activity in isolated cortex when stimulation is not present.

The work referred to above is concerned with animal studies. The similarities between the results of the studies of EEG correlates of behaviour in animals and humans (Wells 1963) suggest that the electrical activity of the brain in the latter group has similar origins. Recently this has been challenged by the suggestion that some components of the scalp recorded EEG do not arise from the cerebral cortex but are a manifestation of activity in the oculomotor system (Bender 1969; Mulholland 1969; Lippold 1970; Lippold and Novotny 1970). Contradictory evidence has been presented by several authors (Brumlik *et al.* 1966, 1967; Miller 1968; Cobb 1970; Shaw *et al.* 1970). It seems unlikely, however, that the cerebral cortex will be displaced as the major origin of the electrical activity recorded from the surface of the scalp.

A major difficulty in studying the electrical activity of the brain is that the measured potentials arise from a multitude of sources, whose extent and exact location within the cortex is unknown. A model frequently used to represent the generators is the single electrical dipole. Its main use has been to represent the source of high voltage focal pathological activity, the known properties of the theoretical dipole being used to interpret a conventional EEG record to locate the focus (Jung 1939). The use of the dipole concept in this way is limited because (i) the volume conduction within brain tissue is very limited so that explanations of widespread events in terms of a deeply located dipole is not possible (Cooper *et al.* 1965); (ii) even when widespread activities appear to represent the same cortical events, there are time differences between similar potential changes in different areas (Hori *et al.* 1969); (iii) there is increasing evidence that EEG activity is due to changes in source configurations (Petsche *et al.* 1970b).

An important extension of the single dipole type of model is to distributions of dipoles or dipole layers (Fourment *et al.* 1965). Such models are closer to the physiological situation in the case of neuronal monolayers, such as the hippocampus which consists mainly of one layer of palisade-like arranged pyramidal neurons. Experiments show that the characteristic activity of this region, "theta" rhythm, is accompanied by corresponding potential changes of the basal dendrites and apical dendrites of opposite polarity, whilst near the soma, no activity is found at all, even during hippocampus seizures (Green and Petsche 1961). The pyramidal cells can thus be represented by vertically arranged dipoles, alternating in polarity with the theta rhythm and the whole hippocampus can thus be considered as a monolayer of parallel dipoles.

Laminar analysis of neocortex (Li *et al.* 1956; Hirsch *et al.* 1961; Calvet *et al.* 1964; Peronnet *et al.* 1972) show that these results can be applied even in this structure. However, the situation is more complex because of the varied lengths of the neuronal "dipoles" and because of the complex curvature of the surface produced by the gyri. Calvet *et al.* (1964) have shown that this causes discrepancies between common reference and bipolar transcortical recordings that were not quite understood previously. These occur because the extent of the dipole layer giving rise to a particular event is not known and also because of the curvature of this layer.

According to the solid angle theorem (Woodbury 1960), the potential due to a dipole layer of constant moment, at a distance from it large in comparison to the dipole length, is proportional to the solid angle subtended by the dipole surface at that point. The validity of this principle was particularly well proven in the curved bipolar layer of the cat's hippocampal pyramids by Gloor *et al.* (1963). It is therefore important to remember the curved structure of the generator layers when recording from the brain surface or from the scalp. This is particularly important when attempting to localize intricate and variable phenomena like slow spike-waves or some sharp wave patterns in children.

Another fact that has to be taken into account when recording from the scalp is that there may be a considerable difference between the ECoG and EEG. This was demonstrated by Abraham and Ajmone Marsan (1958) for epileptiform discharges. Although there is a better correspondence with higher amplitudes, many high amplitude cortical discharges seen in the ECoG are not present in the EEG. The amplitude ratios between EEG and ECoG ranged from 1:2 to 1:58 and the authors conclude from their findings that these differences are mainly due to different sizes of cortical area involved.

Delucchi *et al.* (1962) studied the degree of synchrony in homologous recording sites of both hemispheres in cats. They found that the degree of synchrony was greater in the EEG than in the ECoG. From this and other results they obtained, they concluded that the relatively high conductivity of the CSF acted as an averager of the corresponding electrical fields.

The relationship between the activity at physiological generators and surface electrodes was also studied by Cooper *et al.* (1965) using spontaneous and evoked activity in humans. Their findings agree with those of Abraham and Ajmone Marsan and they conclude that the volume conduction of the brain is very low. Local stimulation of brain tissue produced after-discharges of millivolts amplitude which could not be recorded outside a 0.5 cc volume surrounding the source. When the signal from an oscillator was applied to intracortical electrodes to stimulate a source, the attenuation at a scalp electrode was 1:35,000, even when the generator was exactly below it. The authors conclude that the appearance of activity on the skull probably depends on the degree of synchronization of generators and the area concerned. They regard an area of 6 cm^2 as the minimum required to produce an event that will be seen on the skull.

Further confirmation of the results quoted above and the role of CSF in attenuating cortical potentials is given by the work of Geisler and Gerstein (1961). These authors studied the effect of CSF in both monkeys and in a model. They showed that when a spherical conducting medium containing a dipole was surrounded by a shell of higher conductivity, the result was a considerable diminution of amplitudes, an "averaging" of potentials, and an extension of the apparent area involved in the potential field. According to Bradley and McKelvey (1966) the impedance of CSF at 39° is 45.5 ohm-cm, and the transcortical resistance is 240 ohm-cm. Cobb and Sears (1960) confirmed these findings in hemispherectomized patients, in which part of the CSF was replaced by air. When recording EEGs from these patients, it was found that some activity could be recorded over the hemispherectomized side of the head, and that its amplitude was greater when CSF was replaced by air. The averaging effect of the CSF and surface tissues is also assumed to be the reason for the loss of information when EEG electrodes are put too close together. It may also be the reason why differences of electrical activity between different cytoarchitectural areas seen in lissencephalic brains (Petsche and Šterc 1968) are not seen in EEG recordings from humans.

C. THE MEASUREMENT OF TIME DELAYS

A common characteristic of the topography of EEG signals is that similar events may occur at different electrode sites but not at exactly the same time. Many of the methods described in this part are specifically designed to measure or display these time differences. The word "phase" is often used as a descriptive term to describe these intervals, and instruments for measuring them are often referred to as, *e.g.*, "phase analysers". It is our view that the word phase is wrongly used in this context. It is borrowed from the language of physics and engineering where it has a rather strict definition in relation to sinusoidal or exactly periodic fluctuations. Its use in physiology has arisen because many electrophysiological signals have quasi-sinusoidal or periodic features and so have been analysed in the same way as many physical phenomena. Also different parts of complex patterns of fluctuation in these signals are often described as different phases of the pattern—physiologists speak of diphasic waves, triphasic waves, etc.

In its physical sense, phase refers to a proportion of the wave length of a periodic fluctuation. Usually one period of the activity is scaled into 360° or 2π radians, angle measure being used because of the ease of vectorial generation and representation of sinusoids. Such a description is independent of frequency but in most transmission systems, any change of phase produced by the system is frequency dependent. If two signals have a constant phase difference, the time difference between them will depend on frequency.

Physiological events occurring at different places could be dependent on either phase or time relations. They may be made phase-dependent by the necessity for electrotonic fields to reach a certain amplitude before a neuronal element is triggered, or time-dependent because of the finite velocity of unit discharges in nerve fibres and synaptic delays.

When apparently similar electrical events occur at different sites on the head with a small time difference, the concept of "travelling waves" is often used to describe the observations. Such a description is somewhat controversial (see for instance D. O. Walter and Brazier 1968). In the case of EEG signals, such a concept implies that events have a characteristic physical wave-length in the brain or on the scalp. Foitl and Petsche (1959) and Petsche and Stumpf (1960) have found experimentally several EEG phenomena in which the velocity of "travelling waves" is linearly related to their frequency, wave-length being constant. This in fact implies that at least in several cases time-differences are inversely proportional to frequency and a characteristic that would be called "phase" in the periodic case is constant. The possible functional significance of these time-differences will be referred to in the following discussion. Anticipating this, it can be said that the recent work of Petsche *et al.* (1970b) suggests that EEG signals originate from the time-dependent changes in configurations of the spatial distribution of potential differences, rather than the change in output of fixed sources.

It is therefore difficult to justify the choice of "phase" or "time" as a dependent variable on purely physiological grounds. The classical definition of phase in terms of sinusoids, however, must make its use in EEG analysis a source of confusion except in those cases where components derived by spectral analysis are being considered. We will therefore use the term "time" except in those cases where, in referring to the work of others, it is not possible to substitute "time" for their use of the term "phase".

D. ELECTRODE DERIVATIONS

A fundamental problem for any topographic method of EEG analysis is the choice between the three methods of electrode derivation: bipolar, common reference or common average reference. According to Jami *et al.* (1968), none of these methods is able to represent the true potential distribution of cortical generators according to Woodbury's theorem (1960). The interpretation of EEG topography must take into account the method that is used and this requires an understanding of their particular characteristics. A description of these methods is given by Cooper *et al.* (1969) and some points will be emphasized here.

The *bipolar method* may appear particularly appropriate for topographic work because both electrodes are relatively localized to a particular area. Because of the relative closeness of the electrodes, they are usually regarded as measuring potential gradient. This is a reasonable inference but may easily give rise to incorrect interpretation. For example, if the activity under each electrode arises from the same generator system and with no time-difference, then a straight "gradient" model may be used. If there is a time-difference, then the interpretation is less simple, and in particular apparent time-differences along a line of bipolar electrodes will not indicate true time-differences (Cooper 1959). Interpretation will be even more difficult if the activities under the two electrodes arise from independent sources. The apparent gradient will be due to the algebraic summation of two fields, and patterns of fluctuation which do not correspond to meaningful events may be seen. In these circumstances a correct interpretation will be difficult (Petsche and Frühmann 1966a; Sorel 1969).

It cannot be overemphasized that the *common reference derivation* is also open to misinterpretation because of the possibility that the reference electrode lies close to a source of potential during some part of the recording session. When it is used, care must be taken to eliminate this possibility (Goff *et al.* 1969). Sorel (1969) recommends a site on the neck for the reference electrode, but this often gives rise to an electrocardiogram artefact.

The main difficulty of interpretation with a *common average reference derivation* is that relatively localized high amplitude activity may appear as a widespread distribution of the same activity. Some workers find that using more than one derivation simultaneously helps to overcome ambiguities of this kind and so aids interpretation. Some of the problems of interpreting conventional EEG records in terms of the localization of generators have been discussed by W. G. Walter (1951) and by Dawson and W. G. Walter (1944).