HANDBOOK OF ELECTROENCEPHALOGRAPHY AND CLINICAL NEUROPHYSIOLOGY

EDITOR-IN-CHIEF A. REMOND

VOLUME 10

Direct, Cortical and Depth Evaluation of the Brain

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NINDS, National Institutes of Health, Bethesda, Md. (U.S.A.)

PART C

Electrocorticography

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ELSEVIER

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International Federation of Societies for EEG and Clinical Neurophysiology

A great need has long been felt for a Handbook giving a complete picture of the present-day knowledge on the electrical activity of the nervous system.

The International Federation of Societies for EEG and Clinical Neurophysiology is happy to be able to present such a Handbook, of which this is a small part.

The decision to prepare this work was made formally by the Federation at its VIIth International Congress. Since then nearly two hundred specialists from all over the world have collaborated in writing the Handbook, each part being prepared jointly by a team of writers.

The Handbook begins with an appraisal of 40 years of achievements by pioneers in these fields and an evaluation of the current use and future perspectives of EEG and EMG. The work subsequently progresses through a wide variety of topics—for example, an analysis of the basic principles of the electrogenesis of the nervous system; a critical review of techniques and methods, including data processing; a description of the normal EEG from birth to death, with special consideration of the effect of physiological and metabolic variables and of the changes relative to brain function and the individual's behaviour in his environment. Finally, a large clinical section covering the electrical abnormalities in various diseases is introduced by a study of electrographic semeiology and of the rules of diagnostic interpretation.

The Handbook will be published in 16 volumes comprising 40 parts (about 2500 pages altogether). For speed of publication most of the 40 parts will be published separately and in random order.

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ELECTROCORTICOGRAPHY

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Section I. Introduction

Electrocorticography (ECoG) is the term commonly employed in reference to the technique of recording the electrical activity directly from the human cortex (as well as that of experimental animals). The same term generally includes recording through the dura ("electrodurogram" is a seldom used term), and should apply to both acute and chronic situations; *i.e.*, in case of cortical exposure in the course of neurosurgical procedures, and in the case of chronically implanted electrodes. In practice, however, the term is most commonly used in reference to the acute situations, and will be dealt with here only as such, and only in connection to the clinical applications of the technique. The reader is referred to Volume 10B of this Handbook for the description and discussion of cortical recording in chronic conditions.

Inasmuch as the large majority of brain electrical phenomena which one records through the intact scalp are generated by cells within the cerebral cortex, EEG and ECoG should provide essentially the same data. In principle this is true; however, the two techniques and their indications, possibilities and limitations, as well as the related recording conditions and record interpretation are sufficiently different to justify a separate treatment.

Most of the purely technical differences are obvious and, in the case of the ECoG, are closely related to type of electrodes used and to the situation existing in every major neurosurgical (brain) operation. Other differences, all equally obvious, reflect the topographic extent of the electrographic survey (always more or less limited in the case of ECoG), or deal with the pattern characteristics of the recorded electrical phenomena (unavoidably more distorted and attenuated in the case of the scalp EEG). A further difference between EEG and ECoG is of a rather practical nature: in the case of the latter, the record should always—but for exceptional situations—be obtained directly by a professional, experienced electroencephalographer (rather than by a technologist) and, furthermore, its interpretation has to be extemporaneous and definitive. The technique seldom allows for provisional (*i.e.*, modifiable) opinions, or for re-examinations; not infrequently, this interpretation will influence and guide the neurosurgical decision and possibly lead to irreversible results.

Section II. Brief History and Main References

The direct recording of electrical activity from the human cortex was first attempted at about the same time as the discovery of the scalp EEG. Indeed, the first record from a human subject reported by Berger in 1929 had been obtained by means of epidural electrodes, and a number of records in his subsequent papers were similarly derived from patients with skull defects (see Gloor 1969). In this early period, ECoG was primarily performed to prove the cortical (or brain) origin of the rhythms recorded through the intact skull and scalp and had little or no practical application. In the following years, direct cortical recording was employed occasionally in an attempt to diagnose and localize expanding intracranial processes (Foerster and Altenburger 1935; Schwartz and Kerr 1940; Scarff and Rahm 1941; Petit-Dutaillis *et al.* 1950, etc.). This application of the ECoG technique, however, was soon abandoned due to the unreliability and non-specificity of the slow waves and of localized areas of depressed activity in corticography (see below). Only sporadic studies in the field of brain tumors (see, *e.g.* Hirsch *et al.* 1966) have been carried out in the subsequent years, and up to the present days the main—if not exclusive—indication of ECoG has been in the field of seizure disorders. Specific references are provided in the individual sections of this Part; in addition, the following books or articles include pertinent information and should be consulted by any person interested in the electrographic aspects of surgical treatment of the epilepsies: Walker *et al.* (1946), Marshall and Walker (1949), Green *et al.* (1951), Gastaut (1953, 1954), Penfield and Jasper (1954), Baldwin and Bailey (1958), Jasper *et al.* (1961), Cernacek and Cigánek (1962), Magnus *et al.* (1962), Bates (1963).

Section III. Technique

A. PHYSICAL ARRANGEMENTS AND EQUIPMENT LOCATION

The positioning of the recording and stimulation equipment varies in relation to the physical characteristics of the operating area and depends upon the existing facilities; occasionally it might be determined by the specific training of the neurosurgeon and the availability of a specialized professional team.

In some centers all the main equipment is situated directly in the operating room, often in close proximity to the neurosurgeon or within his field of vision. In most centers, however, both stimulation and recording devices, or at least the latter, are located in a separate room, outside the sterile field. In the former situation, the neurosurgeon himself might assume the responsibility for—or closely supervise—the interpretation of the tracing which, in such case, can also be obtained by a skilled technologist. When the equipment is located outside the immediate operative field, the recording procedure and interpretation become the sole responsibility of an experienced, professional electroencephalographer. In this situation, however, it is important to secure and maintain the best uninterrupted visual and auditory communication between him and the neurosurgeon. In particular it is important for the electroencephalographer to have a clear and detailed view of the operative field at all times, while it is preferable, though less crucial, that the neurosurgeon have the possibility of monitoring the record as it is being run. In the early times, this visual communication could be achieved by a strategic placement of the recording devices, generally as close as possible, and at an appropriately higher level in relation to the operative field, with a wide (and solid) window in between. In optimal situations, the electroencephalographer would be only 2–3 meters away from the patient's head and thus be able to see at all times (if necessary with the help of binoculars) the exposed cortex and to follow its surgical manipulations and the actual positioning of the electrodes in fairly good detail. A system of appropriately placed mirrors would give the neurosurgeon the possibility of viewing the record. With the advent of television and the commercial availability of color TV sets and closed-circuit systems, the problem of visual communication between neurosurgeon and electroencephalographer has been greatly simplified. In particular, it is now possible to provide the former with a continuous, optimal display of the record through a conveniently placed screen while the recordist can monitor the record and, simultaneously have a close-up of the operative field through another screen placed in front of him. Although television has made the physical location of the recording room less crucial, it is still preferable to have the latter adjacent to the operating room with the possibility of direct visibility between the two. Auditory communication is generally achieved, quite satisfactorily, by means of an inter-com system. Preferably, the circuit of the latter should include a secretary (and/or a magnetic tape recorder) and permit the inclusion (or exclusion) of patient and anesthesiologist.

B. RECORDING EQUIPMENT

The apparatus of ECoG recording does not differ, in its essential characteristics, from that used for scalp EEG. The following considerations are, however, in order.

The necessity for "high fidelity" equipment—when this is intended for exclusive use in routine clinical EEG—is somewhat questionable. Indeed, in the field of scalp EEG one is mainly dealing with signals which are either already greatly distorted at their pick-up level, or are of extracerebral origin. Thus, all the features increasing the fidelity of the amplifying and transcribing equipment would mainly result in better reproduction of these distortions or in enhancing interferences and irrelevant signals. The situation is more favorable in the case of ECoG, where the pick-up electrodes can be placed closer to the source of the signals, without the interposition of inert or active extracerebral tissue, and where interferences of extracerebral origin are greatly reduced. In this situation there is, therefore, a definite advantage in using amplifying and recording equipment of a relatively higher fidelity. This concerns primarily the frequency response of the apparatus. Whereas the main frequencies of the background rhythms in ECoG are in the same range as those of scalp EEG (*i.e.*, their upper limit seldom exceeds 40–50 c/sec), direct recording from the cortical surface may include transients of much briefer duration and steeper slope than in the case of scalp recording. The overall form of such transients—whose origin is unquestionably cerebral—would be distorted, and their amplitude decreased by an amplifying and recording system with a poor frequency response, or by a system in which such response had been purposely decreased by filtering off the upper frequency range. On the other hand, the lower band of frequencies (delta) appears to be less crucial in ECoG, and the overall time constant of a recording instrument does not need to be much longer than that available in most EEG apparatuses (0.3–1 sec). This conclusion stems from practical considerations. As will be mentioned later (see Artefacts, p. 10C-17), there is in ECoG a much greater number of factors (both biological and physical) which are capable of producing large sways of the baseline, or slow activity in general, than in scalp EEG. Thus, a DC instrument, or one with a very long time constant, would only yield a record in which various spurious slow potentials of questionable pathophysiological significance were unnecessarily prominent.

Another practical reason for not emphasizing the need for ECoG amplifiers with very long time constants, is that blocking phenomena are generally more prominent and of longer duration in such amplifiers. Since cortical electrical stimulation is an important aspect of the overall ECoG procedure and is carried out, routinely, while the recording goes on (and in close proximity to the pick-up leads), blocking of the amplifier can represent a serious handicap for a satisfactory continuous monitoring of the cortical activity and, in particular, of the immediate post-stimulation effects (see below). Thus, an ideal ECoG amplifier should have the shortest possible blocking time (and a relatively short time constant tends to contribute to its decrease). The problem of a long blocking time would be eliminated by using recording equipment with DC amplifiers, but these are seldom available in commercial EEG machines and, beside, this type of amplification might not be practical in view of what has already been mentioned about the excess of spurious slow activity in ECoG.

It should be emphasized here that most of the preceding considerations are applicable to the equipment for ECoG only when its primary purposes are of an exclusively diagnostic nature. It is obvious that when the technique is used also—or mainly—for specific research projects, more sophisticated amplifying equipment is preferable, and other methods of display (cathode ray oscilloscope, magnetic tape, etc.) might be better than conventional ink-writing devices.

The optimal number of channels in an EEG apparatus is generally considered, nowadays, to be 16. Such a number allows for a reasonably complete, simultaneous survey of the activity of both hemispheres, while a larger number would often be redundant. In spite of the fact that the area of the field available for ECoG investigation is considerably smaller (one fourth or less in most standard procedures) than that for scalp EEG, the availability of a relatively large number of channels is highly desirable in ECoG equipment. Indeed, in direct cortical recording—and at variance from scalp EEG—many electrographic phenomena can be exquisitely localized within areas of a few square millimeters (see, *e.g.*, Fig. 13*B*, *C* and 15*A*). As a consequence, for a thorough survey of the exposed cortex, a large number of electrodes is required or their placement has to be frequently rearranged. If the recording equipment consists of numerous channels there is less need for a frequent change of electrode positions and runs, and precious time can be saved by the neurosurgeon.

C. ELECTRODES

These are generally mounted in a holder that can be easily fixed to the bone. Such an electrode set should: (a) be sterilizable; (b) be quickly applicable and quickly removable; (c) permit a clear view of the cortical field and not interfere with its surgical manipulations; (d) ensure a good electrode contact with any portion of the exposed cortex and (e) permit an easy identification of faulty leads.

Different types of such sets have been described in detail or are illustrated in the papers by Walker *et al.* (1946), Jasper (1954), Pampiglione and Cooper (1955), Bates (1963) etc., and some, manufactured by specialized firms, are commercially available. An example of a set which is used in our Institute (and which is based on that originally designed for the Montreal Neurological Institute) is shown in Fig. 1. Each set consists of a certain number of electrodes (minimum 8 but preferably 16 or more). The electrodes are generally mounted on a straight or semi-circular (horse-shoe shaped) bar which is placed at the border of the exposure, or they are inserted in a plate made of transparent material which can be located over the exposed area. The former models have the advantage of leaving greater freedom for surgical manipulations and offer less interference to a roving electrode for stimulation (see below),

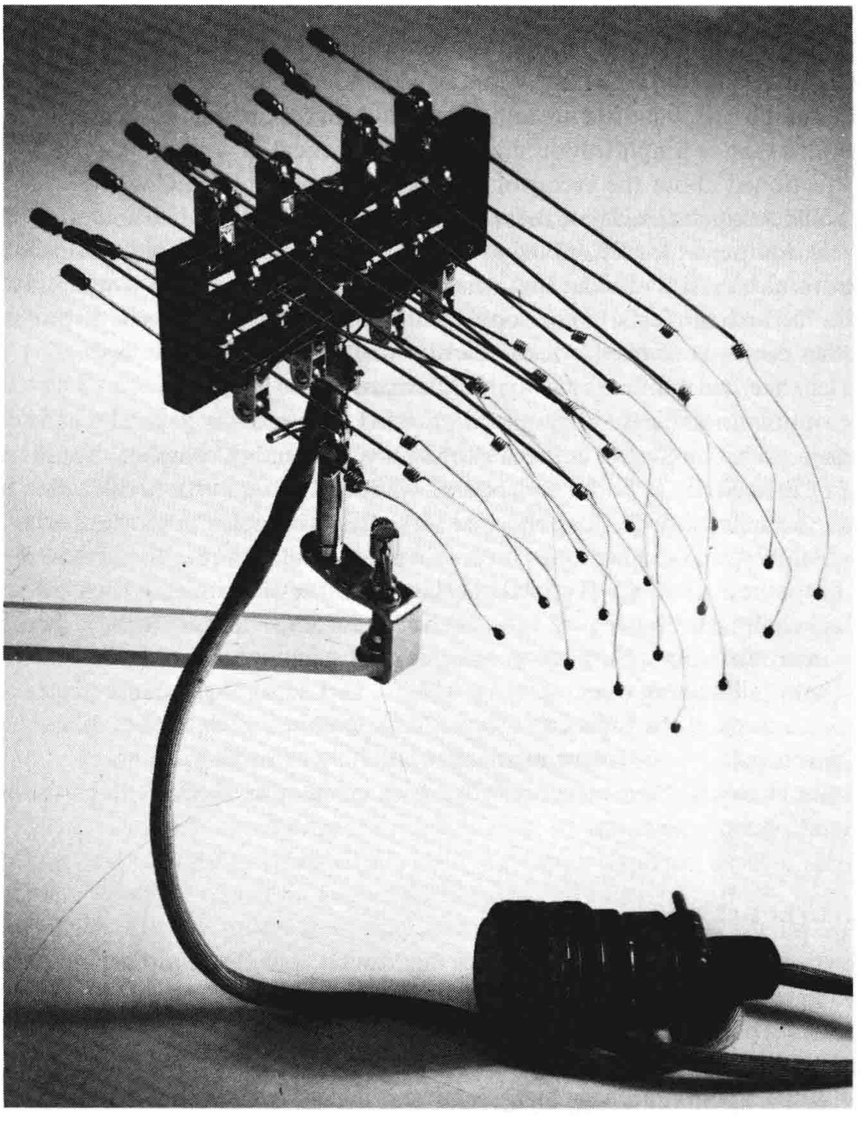


Fig. 1. Electrode set for ECoG (16 contacts). Type used at the National Institute of Neurological Diseases and Stroke, NIH. Modified from the original set designed at the Montreal Neurological Institute.

while permitting a clearer and undistorted view—and photography— of the field. The latter model facilitates the placement of the electrodes for a complete survey of the entire cortical area and makes it easier to identify individual electrode positions. Regardless of the model and type and shape of the holder, it is important that each electrode be mounted in such a way as to ensure both perfect electrical contact and maximal flexibility of its orientation and placement, with minimal chances of interferences between the numerous electrodes which are necessarily crowded in close proximity to each other over a relatively small area. Thus, with a satisfactory set it should be possible to place each individual electrode at any point of the exposed field. This requires good lateral and vertical rotation of the electrode axis and the possibility of modifying the electrode length within a useful range. In practice this can be achieved, for instance, by mounting each electrode shaft in a ball or universal joint which is held by (but can rotate around or within) a metal peg or socket, fixed to the holding bar or plate, and through which the electrode shaft itself can be slid up and down and rotated. By critically adjusting the tightness of these two junction points, each electrode can be properly oriented and placed, as well as maintained in any desired position. The electrode shaft is generally a rigid steel tube into which the actual electrode (a silver or platinum wire carefully insulated down to its tip with any type of appropriate, heat resistant varnish) is inserted and cemented. This wire exceeds the length of the shaft by about 5–7 cm in its distal portion and, since it is light and malleable, it can be easily bent and adjusted at any selected place without interfering with the placement of the other electrodes. A few turns twisted in the proximal portion of the exposed wire may add to it a spring-like effect and increase the range of its length modification. A satisfactory, steady electrical contact between electrode and cortical surface, with minimal risk of damaging the latter, can be achieved by a ball-shaped tip and by covering such tip with a small cotton wick soaked in saline solution[1]. Electrodes consisting of a carbon tip are used in several laboratories. Such electrodes are apparently very stable and yield artefact-free records.

Other types of electrodes or electrode sets can, of course, be used (see, *e.g.*, Le Beau *et al.* 1959). When one wishes to monitor simultaneously the activity of a small area from a relatively large number of points, one could utilize the multiple electrode arrays of the type more commonly used in chronic cortical recording. Models of such arrays, in which the electrodes are embedded in a transparent plastic sheet, and which can be constructed with the principles and materials of miniature flexible printed circuitry, have been described by Cohen (1961) and by Hanna and Johnson (1968). These models ensure a fairly satisfactory contact but have minor disadvantages: (a) interelectrode distance and electrode arrangement are pre-set and cannot be modified; (b) the visibility of the field and the possibility of its surgical manipulation are somewhat limited, and (c) the area available for direct stimulation by means of a roving electrode is

[1] Before use, and at given intervals thereafter, silver electrodes must be chlorided to render the junction non-polarizable. A detailed description of the chloriding procedure can be found in the chapter by Walter and Parr (1963). Also important is to test at frequent intervals the electrode set in saline to check for break in continuity, faulty or insufficient chloriding, noise, etc. For this test, the electrodes are first rinsed in saline; the tips are then immersed in a large glass container with 1–2% saline solution, taking care that they are not in direct contact with each other and that they are completely immersed in the solution. The set should be firmly secured to the container, and this should be placed on a firm stand to avoid movement of electrodes or fluid. The electrodes are then connected to the amplifier in bipolar or referential fashion, and a record obtained at slow speed, with a sensitivity greater than that used during the actual ECoG recording. Satisfactory electrodes should yield a straight line tracing, continuously, for at least 10–15 min. If slight irregularities are present from one or several electrode pairs, the electrodes should be cleaned again with acetone-soaked cotton and rinsed in clear water or saline, after which the recording procedure should be repeated. If slow sways of the baseline are still present after 15–30 min of recording, the electrodes need chloriding. During the saline test, it is also advisable to tap all junctions and connections from electrode tip through terminal plug, to check for loose connections or partially defective cables.

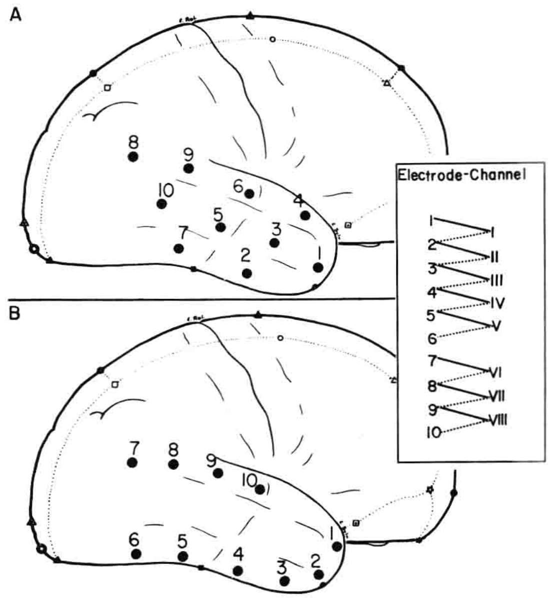


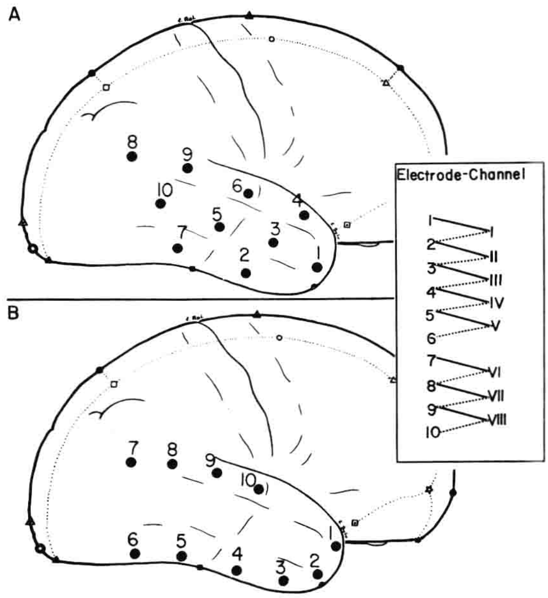
Fig. 2. Examples of electrode placement and bipolar montage with a set of 10 electrodes and an 8-channel recording apparatus in a hypothetical case of temporal lobe exposure. *A*: poor electrode placement. *B*: more logical placement (see text).

identification, speeds up the composition of runs and their combination by the electroencephalographer and, chiefly, simplifies his extemporaneous interpretation while minimizing the chances of errors. The main goal is to survey as thoroughly as possible the entire area of exposure, but there are practical advantages in doing such a survey with some systematic order and, preferably, by following the same principles in every case. There are, of course, various orders of electrode arrangement one can select—all rational and acceptable—and, indeed, it is always advisable to survey the same region(s) by different combinations of runs. There is some advantage, for instance, in using the main fissures and convolutions as a guide for the electrode placement, numerical order and runs. On this principle, the temporal convolutions are satisfactorily surveyed by means of antero-posterior (or postero-anterior) electrode sequences (*e.g.*, electrodes 1, 2, 3, 4 along the first; 5, 6, 7, 8 along the second and 9, 10, 11, 12 along the third convolution; electrodes 1, 5 and 8 being at the tip of the temporal lobe, etc.). A medio-lateral (or lateromedial) sequence is also suitable, especially for the survey of the pre- and post-Rolandic gyri (*e.g.*, electrodes 1, 2, 3, 4, 5 along the post-central gyrus from the midline toward the Sylvian fissure, and 6, 7, 8, 9, 10 along the pre-central gyrus in the same—or opposite—direction, etc.).

These considerations are valid regardless of whether one plans to record with bipolar or referential montages. In the former case, the numerical order of the electrodes in the sequence is, of course, very important for a rational montage (Fig. 2) and for a quick identification of individual electrodes and localization of abnormalities, but the same order also simplifies the interpretation in the case of referential recording. In practice, both techniques should be used, either in the same or in sequential runs.

In the placement of electrodes in scalp EEG, one recognizes the importance of symmetry and equidistance, and the widely accepted "International 10–20 system" (Jasper 1958a) is essentially based on these two principles. In the case of ECoG, the opportunity or need for a "symmetrical" arrangement of electrodes seldom arises. Due to the relatively large variation in the areas of exposed cortex in different cases, one cannot rigidly adopt a standard distance between electrodes, but this should be kept reasonably similar and comparable among electrode pairs, whenever bipolar recording is used. With this technique, one should preferably avoid recording from pairs of electrodes which are less than 1 cm apart. On the other hand, electrodes do not need to be equidistant, and can be separated by only a few mm, when the recording is referential: indeed, one has little choice but to use this technique whenever the area of exposure is limited and/or the electrodes are crowded over an area of a few square centimeters. As mentioned above, electrical events can be exquisitely localized in ECoG, but the continuous spray of physiological solution which is required to keep the exposed surface moist often results in pools of conducting medium with shunting effects between two adjacent electrodes, and a consequent equipotential record. This situation occurs more commonly than one might expect, with the creation of apparent "foci" of depressed activity or spurious flattenings of the tracing, even when the two electrodes of the pair in question seem to be separated by a reasonable distance. In view of this, one should interpret with great caution such findings when recording with a bipolar montage, and any suggestion of local areas of depression should, in any case, be confirmed by referential recording. Indeed, the main practical reason for not using routinely—or even exclusively—the latter technique, is the difficulty of selecting a satisfactory placement for the reference electrode. Truly inactive points are generally sources of artefacts, and artefact-free locations are seldom totally inactive. Since the main indication for ECoG is in the field of "focal" seizure disorders, it is almost always possible to utilize as points of reference one position of the exposed cortical area which—though not absolutely inactive—can be considered so, as far as epileptiform activity is concerned (see, *e.g.*, Fig. 3*A*, 6*C*, 7*B*, 8, 10). In such case one should not ignore, of course, the potential contribution of the reference electrode to the background activity. In sporadic situations one can utilize as indifferent point for placement of the reference electrode an area of gross pathology truly deprived of electrical activity (*e.g.*, as in Fig. 5). In the experience of some investigators, a clip which grips the bone edge represents a most satisfactory referential electrode. The dural surface, at the periphery of the excision, or a cut muscle might also be used, but such placements seldom provide an artefact-free record. Equally unsatisfactory, in our experience, is the use of a reference electrode fixed to the contralateral earlobe prior to the operation.

It is in general good practice to rearrange the electrode position at least two or three times before considering the (pre-excision) recording session as complete. The number of positions required for a satisfactory exploration depends on the complexity of the case, the number of electrodes available in any given set, the area of exposed



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