COMPARISON OF SUBCORTICAL, CORTICAL AND SCALP ACTIVITY USING CHRONICALLY INDWELLING ELECTRODES IN MAN

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Considering the number of publications concerning the significance of the EEG recorded from scalp electrodes, there are surprisingly few comparing subcortical, cortical and scalp activity. The relationship of the potential fields on the scalp to the underlying cortical activity is still imperfectly known and the lack of a satisfactory theory for the generation and transmission of subcortical and cortical electrical activity is a severe handicap in the clinical application of the modern sophisticated recording equipment and methods of analysis.

Early publications concerning the genesis of the EEG almost always included drawings of dipoles and associated fields in which the dipoles were usually suspended in mid brain. Implantation of intracerebral electrodes, first in animals and then in man, showed that the field spread (volume conduction) inside the brain is very small (see, for example, Sem-Jacobsen 1955) and that the potential differences due to dipoles suspended in mid brain would not be observed on the scalp unless the dipole voltages were much higher than those ever found in brain tissue (Cobb and Sears 1960).

The problem of the mechanisms of the electrical transmission of the EEG was reviewed in detail by Cobb (1957), whilst considering the EEG abnormalities at a distance from a lesion. In this review physiological transmission was considered to be much more important than volume conduction, although it was pointed out that the scalp EEG is only possible by field spread through the skull and scalp.

Abraham and Ajmone-Marsan (1958), studying the transmission of seizure waveforms observed in temporal lobe epileptics, showed that much cortical activity is not seen on the scalp although at times there was high correlation between the cortical and scalp activity, with little attenuation. A more recent paper by DeLucchi *et al.* (1962) showed that, in animals, the scalp acts as a spatial averager of electrical activity, transmitting those components which are common to and synchronous over relatively large areas of the cortex.

The purpose of this communication is to support and extend these results from observations of humans with implanted electrodes and to assess the significance of the scalp EEG in the light of this information.

The use of chronically implanted electrodes in man for psychiatric and other purposes is well established (Crow *et al.* 1961; Walter and Crow 1964). Fortunately, various procedures which are an essential part of the investigation and treatment of these patients at the Burden Neurological Institute also provide unique opportunities for comparing intra- and extracranial electrical activities.

The records reproduced here are representative of many observations on twelve patients. Most of the recordings were from intracranial gold electrodes 2–4 mm long and 0.006″ (150 μ) diameter. Scalp electrodes were usually silver/silver chloride discs (1 cm diameter) and in two cases subcutaneous gold electrodes were used. The records were taken on an Offner Type T or TC EEG machine, using a time constant of 1.0 sec, except where stated otherwise.

RESULTS

1. *Spontaneous electrical activity*

It is well known that, with present techniques and methods of analysis, decreasing the distance between scalp electrodes below a few centimetres

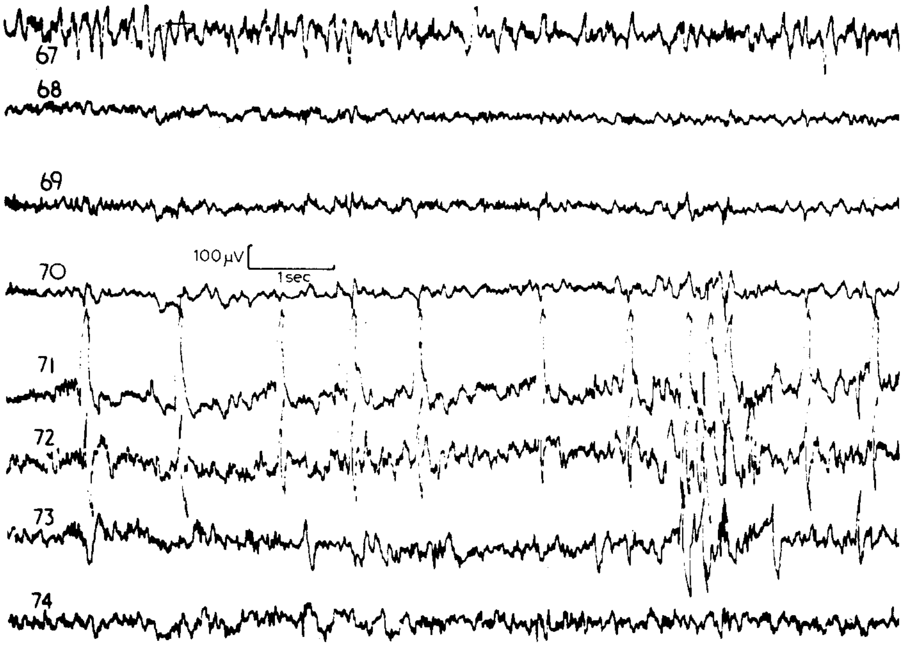

Fig. 1a
Electrical activity from 8 intracerebral electrodes referred to the average of 60 electrodes in frontal, temporal and occipital regions. The record shows different activities in all channels and demonstrates the lack of field spread (volume conduction). Electrodes 68 through 73 are each 4 mm long, tips separated by 8 mm.

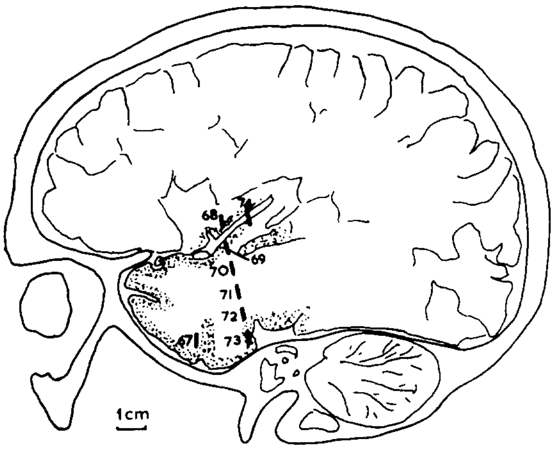

Fig. 1b
Electrode positions of Fig. 1a. This and other diagrams of electrode positions are drawn from X-ray photographs and sections taken from the brain atlas of Delmas and Pertuiset (1959). The section is 40 mm from midline.

does not give additional useful EEG information because the electrical activities recorded from closely spaced electrodes are very similar. In marked contrast, recordings from intracerebral and cortical electrodes can show differences from millimetre to millimetre.

Fig. 1a shows the electrical activity recorded from electrodes in the temporal lobe of an epileptic patient. The positions of the electrodes are shown in Fig. 1b. Electrodes 71, 72 and 73, each 4 mm long, with tips separated by 8 mm, show very different wave forms although the occurrences of the transients are clearly related. None of this activity was seen in records from scalp or sphenoidal electrodes. Fig. 2 shows recordings from frontal subdural electrodes spaced as shown. Although the tips of electrodes 4 and 5 were separated by 3 mm and the spacing between contacts was only 1 mm there is a marked difference between the electrical activities derived from these almost contiguous regions.

Another feature of the intracranial recordings, observed by all users of implanted electrodes, is the lack of "eye-artefact" even though the intracranial electrodes may be nearer to the eyes than scalp electrodes which show large potential changes associated with eye movement (Fig. 2).

Electrodes placed on the scalp very close to

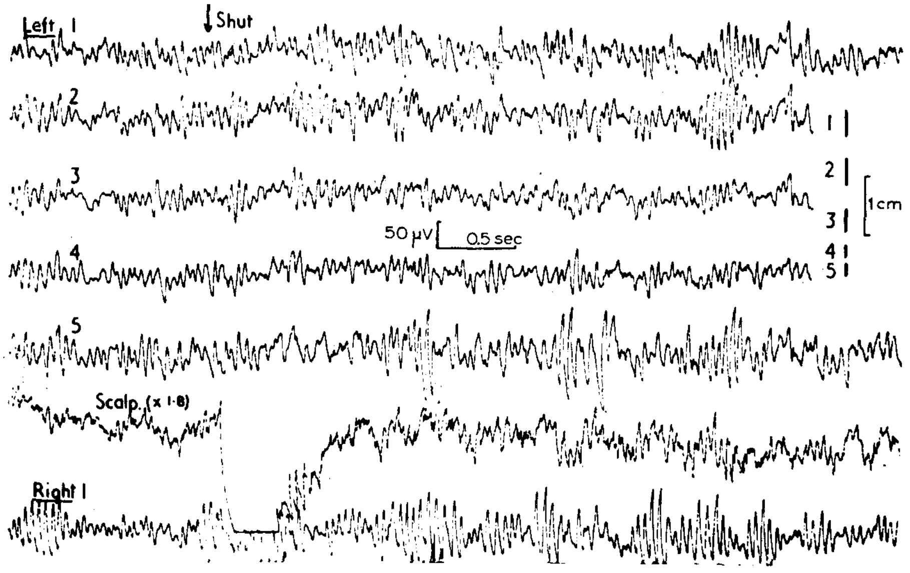

Fig. 2
Recordings from closely spaced left subdural electrodes, scalp electrode F3 above these subdural electrodes, and one right frontal subdural electrode. The spacing of the left subdural electrodes is shown. All recordings referred to average of 60 electrodes in frontal lobe. All channels showing different activity even though the gaps between electrodes are only a few mm. Note absence of eye artefact in subdural recordings and lack of obvious similarity between subdural and scalp recordings.

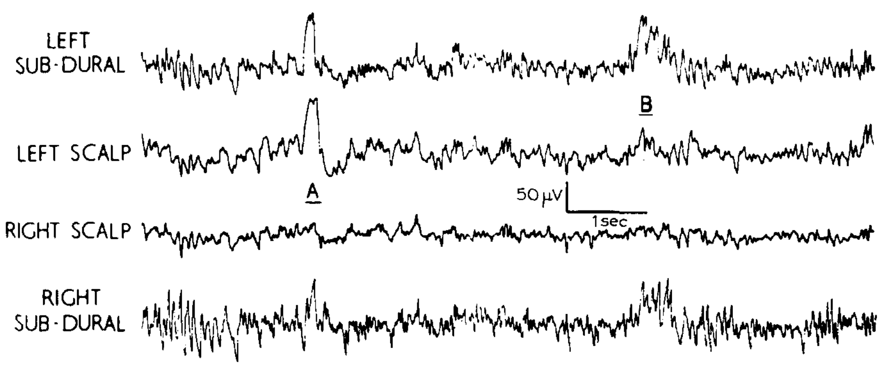

Fig. 3
Comparison of subdural and scalp recordings. All channels referred to average of 60 electrodes in frontal lobes. Scalp activity sometimes shows similarities to subdural but often bears little resemblance. Scalp electrodes about 3 cm posterior to F3 and F4.

subdural electrodes sometimes show electrical activity similar to the cortical activity but often show little apparent relationship, as seen in Fig. 3. A large transient (*A*) is very similar in form and amplitude at left scalp and left cortex although (*B*), a similar transient on the same subdural electrode, is not obvious on the scalp. Neither of these transients is recorded from the right scalp electrode although the right subdural electrode does show related transients with different wave forms at these times.

The average amplitude at the cortical level is usually not more than two or three times that at the scalp and we have found no evidence to suggest that the EEG on the scalp is primarily due to *unusually large* signals at the cortical level.

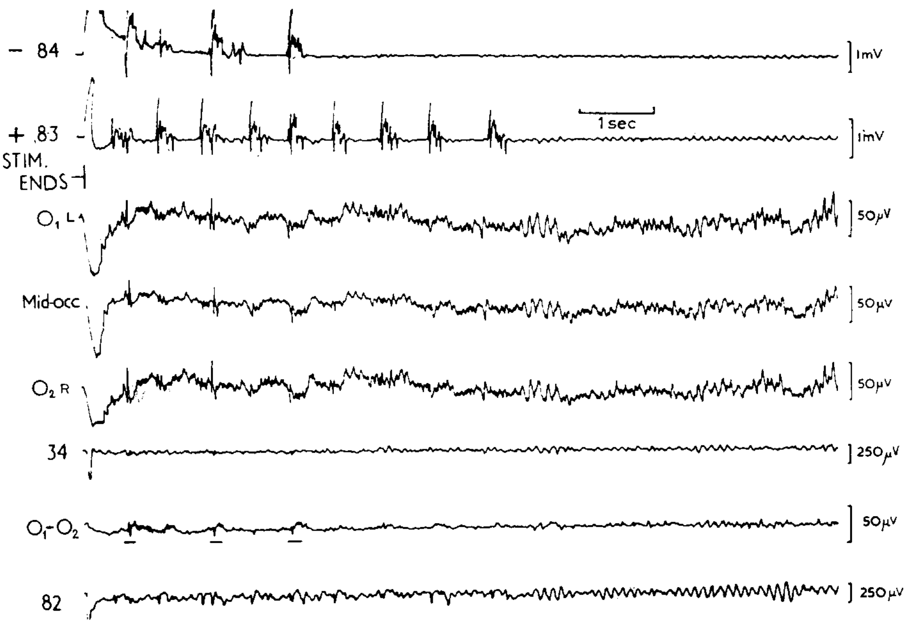

Fig. 4a

Lack of scalp activity from localised high voltage cortical after-discharge. All channels except 7 referred to average of 60 frontal and temporal intracerebral electrodes. Note the large differences in gains.

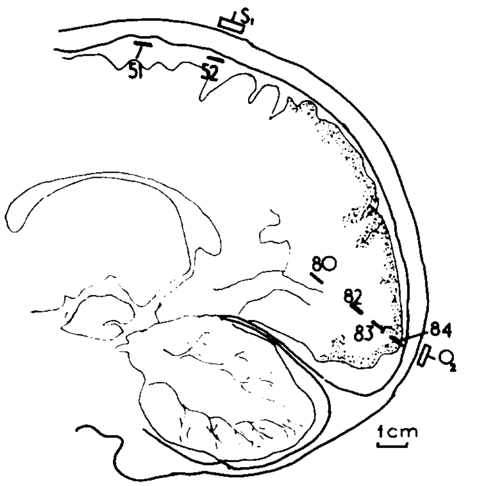

Fig. 4b

Position of electrodes used in Fig. 4a. The section is 18 mm from midline. Electrodes 32, 33 and 34 are in the left hemisphere in symmetrical positions with 82, 83 and 84.

2. *Activity evoked by electrical stimulation*

One of the characteristics of electrodes lying in cortical grey matter is that electrical cathodic, and occasionally anodic, stimulation can be followed by a localised after-discharge similar to that described by Chang (1959). Such stimulation has been found useful for identification of grey and white matter prior to electro-coagulation in psychiatric patients (Crow *et al.* 1961).

In most patients the after-discharge is very localised; electrodes in tissue a few millimetres from the stimulated electrode usually show no sign of the after-discharge. The inference is that, although they may reach voltages of several millivolts, these after-discharges involve only a very small volume of tissue, probably of the order of less than 0.5 cu.cm.

Fig. 4a shows a typical after-discharge following stimulation through intracerebral electrodes in the occipital region. In this record independent after-discharges are seen at the electrodes which were anode and cathode, 83 and 84. Electrode 84 was lying in cortex very close to the dura immediately beneath scalp electrode O_2, electrode 83 was 8 mm anterior to 84 and electrode 82 was 8 mm anterior to 83 (Fig. 4b). Electrode 34 was a cortical electrode beneath scalp electrode O_1. Except for channel 7, which was bipolar O_1–O_2, all electrodes were referred to the average of 60 intracerebral electrodes in frontal and temporal

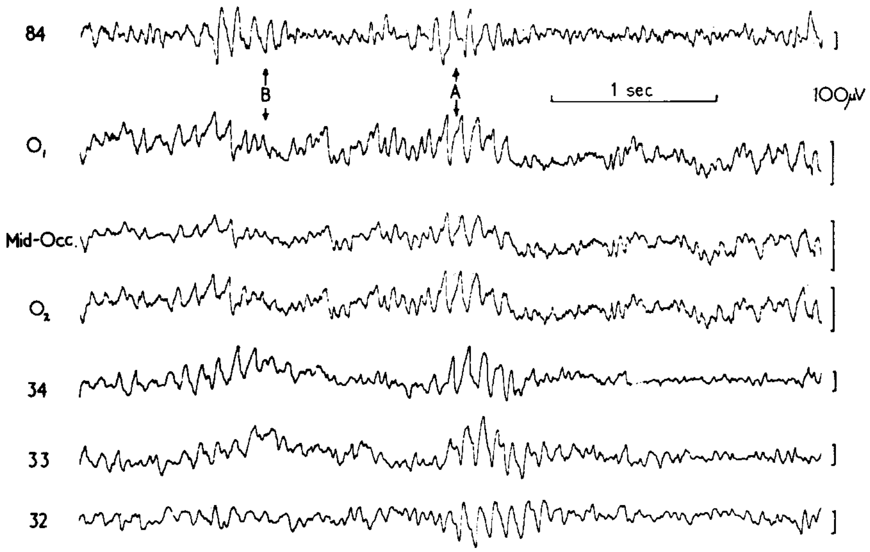

Fig. 5
Alpha rhythms recorded from electrodes as in Fig. 4 but with different gain settings. The amplitude of the scalp activity at *A* is ⅓ of the cortical activity at electrode 84. At *B* the alpha activity at electrode 84 is not observed on the scalp.

lobes which, for the electrical activity described here, may be considered electrically inactive.

The amplitude of the two independent after-discharges, which consisted of multiple spikes and a slow wave, was 1 or 2 mV. The true amplitude of the slow wave must have been much larger than that seen on the record because of the inherent time constant of the small gold electrodes (Cooper 1962) and the short EEG machine time constant (0.03 sec), used so that recordings could be observed soon after the end of stimulation.

Channels 1, 2, 6 and 8 show that there was no appreciable spread of electrical activity over a distance of 8 mm separating electrodes 83, 84 and 82, nor to the opposite hemisphere, electrode 34. There was, however, a small signal at *all* scalp recording positions in synchrony with the grouped activity on electrode 84, but the waveform was not the same, the slow wave being much more attenuated than the spikes. Although the scalp spike activity was seen on O_1,O_2 and the midline occipital electrode the amplitude was slightly larger on the right occipital electrode, as is shown by the signal in the bipolar derivation, O_1–O_2, channel 7. Comparison of the amplitudes of signals from scalp and intracerebral electrode 84 shows that there is an attenuation factor of about 40 : 1 of the spike component of the after-discharge, with a much larger but unknown factor for the slow wave.

However, the 40 : 1 attenuation factor does not apply to the *spontaneous* alpha activity observed at these electrodes. In Fig. 5 the group of alpha waves at *A* seen in the scalp and cortical recordings is attenuated only threefold. In this patient scalp alpha activity was always accompanied by alpha activity at electrode 84 but, as is shown at *B*, the occurrence of alpha activity at this electrode did not mean that alpha activity would be observed on the scalp. It will be noted that the intracranial alpha activity at *A* is much more widespread than that observed at *B*.

In one patient the after-discharge evoked by stimulation through electrodes in the cingulate gyrus was more widespread and prolonged. Fig. 6a shows a sample of the recording of this after-discharge, which was smaller than usual; it was evoked by bipolar stimulation through electrodes 32(−) and 33(+), which were 8 mm apart. The recordings from these and other electrodes shown were referred to the average of 40 intracerebral electrodes in the frontal lobes. The left subdural electrode, channel 4, to which the after-discharge spread in a modified form, was 30 mm above the stimulation electrodes, Fig. 6b. The right

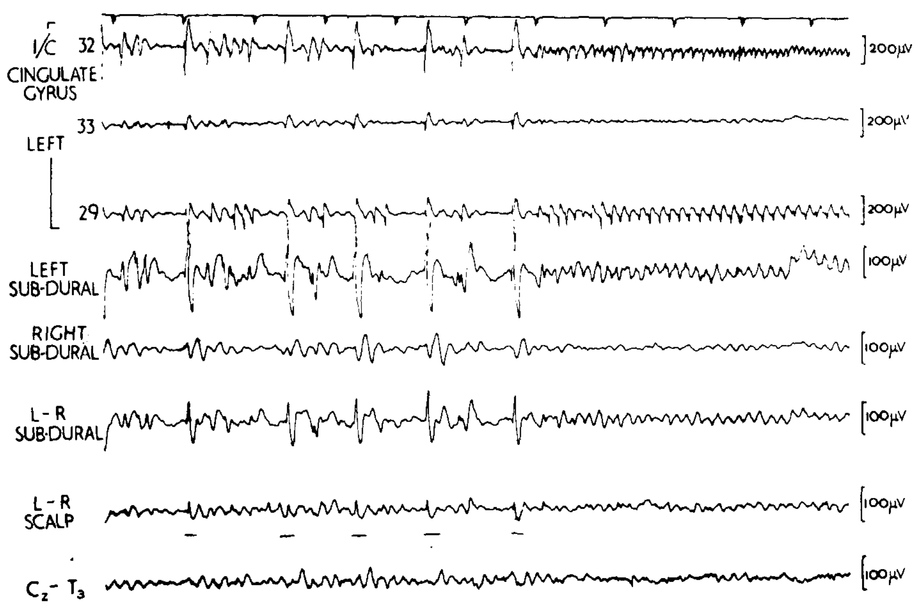

Fig. 6a

Appearance of scalp activity (Ch. 7) when a large cortical area is involved in after-discharge. The amplitude of the subdural activity (Ch. 6) is about three times that observed on the scalp (Ch. 7). Except for bipolar recordings all electrodes are referred to average of 60 electrodes in frontal and cingulate regions.

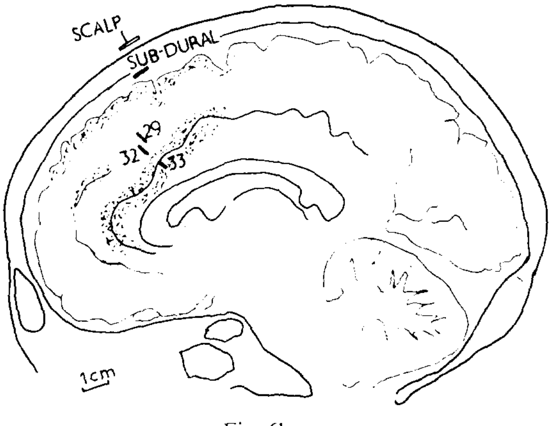

Fig. 6b
Position of electrodes in Fig. 6a.

subdural electrode also shows rhythmic activity related to the after-discharge, but of smaller amplitude. Bipolar recordings from scalp electrodes, immediately above the subdural electrodes (3 cm posterior to F3 and F4), show an attenuation of the activity of about 3 : 1, whilst the vertex electrode (C_z–T_3) shows little or no activity related to the after-discharge.

3. *Electrical activity evoked by sensory stimulation*

The activity evoked by single flashes of light recorded at electrode 84 (Fig. 4b) was compared with the activity recorded from scalp electrode O_2.

Ten flashes were presented at irregular intervals and the responses, recorded on a two channel C.R.O., were photographed superimposed. The upper photograph in Fig. 7 was taken with the subject's eyes open and the middle photograph with eyes shut. The upper trace of each pair shows the cortical response and the lower trace the scalp response. The recordings from subcutaneous electrodes in the scalp were very similar to the scalp recordings.

The cortical response (upper trace) with eyes open consists of a positive deflection of about 200 μV, not seen in the scalp recording (lower trace), which shows a small coherent rhythmic response. The smaller cortical response with eyes closed again differs from the scalp response, in which a coherent after-rhythm is particularly clear; this is presumably because the scalp lead

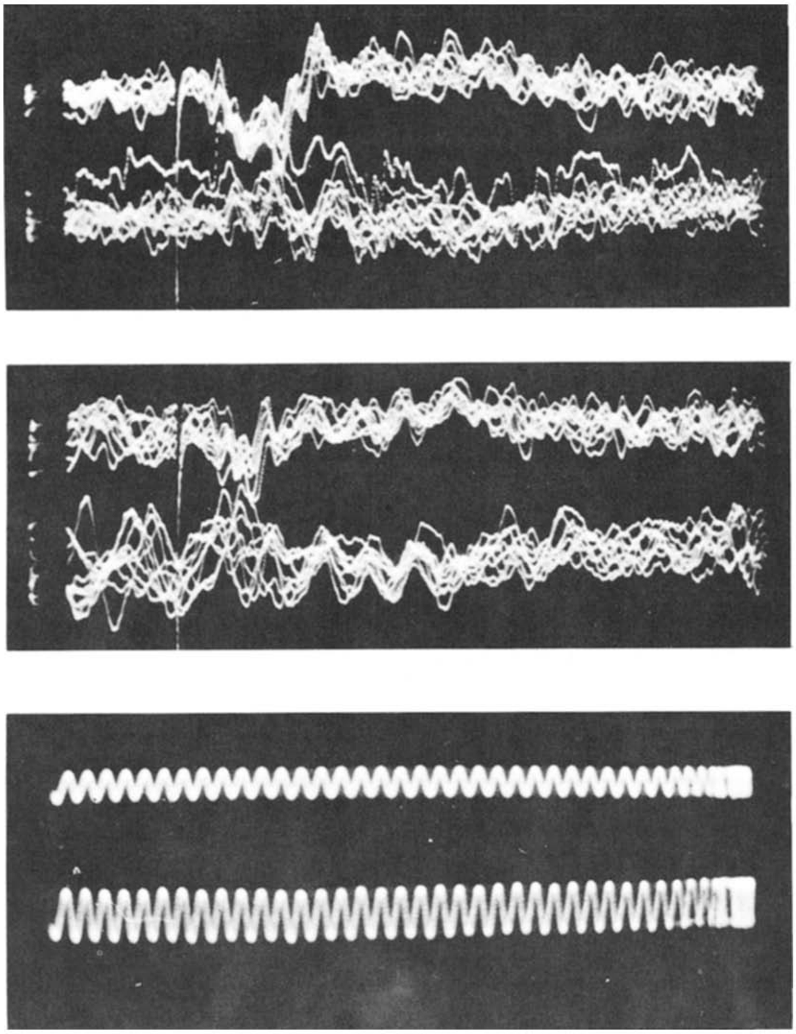

Fig. 7
Comparison of flash-evoked scalp and cortical responses by superimposition. Upper trace: cortical response (electrode 84, Fig. 4b), lower trace: scalp response (O_2). Upper photograph — eyes open, middle photograph — eyes shut. Calibration 100 μV, 50 c/sec.

collects the synchronised responses from a large area of cortex.

In contrast to these differences, seen regularly in specific sensory areas, recordings of the responses to sensory stimuli in non-specific regions, using frontal scalp and subdural electrodes, show marked similarities. Fig. 8 shows the scalp (3 cm posterior to F3), subdural and frontal intracerebral responses to clicks. The amplitude of the scalp response is about half that observed on the subdural electrodes and is about the same size as the widespread frontal lobe intracerebral responses. The intrinsic cortical beta activity, however, does not appear at the scalp electrodes.

4. *Electrical activity on the scalp from artificial intracranial generators*

In the first cases of chronic implantation of intracerebral electrodes it was thought that, as a supplement to radiography, the position of the electrodes could be determined using scalp location methods when an external sine wave oscil-

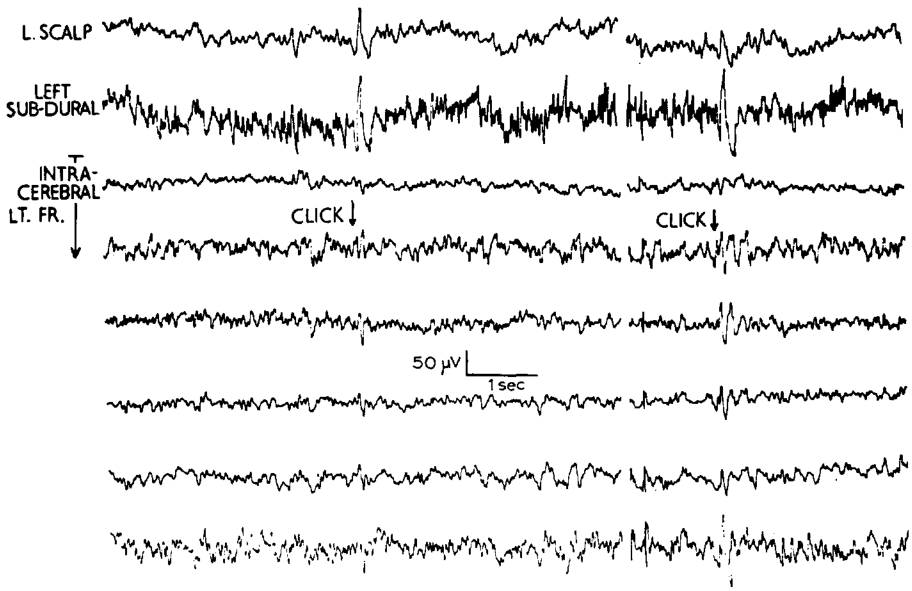

Fig. 8
Small attenuation of widespread non-specific response. The amplitude of scalp response about half of cortical response. All electrodes to average of 60 electrodes in frontal and cingulate regions. Note the absence of the subdural beta activity in scalp recording.

lator was connected to the intracerebral electrodes. Unfortunately, it was found that large voltages (about 2 V peak to peak) had to be applied before any activity whatever could be observed on the scalp, even though one of the generator electrodes might be lying in the cortex directly beneath the scalp electrodes. For example a 25 μV signal was observed on the scalp (O_2-F_2) when an 850 mV sine wave was applied to electrodes 80 and 84 shown in Fig. 4b, an attenuation of 35,000 : 1. Similar attenuation was found when electrodes 83 and 84 were used as the artificial generator. Even sub- and epidural electrodes were difficult to locate by this method and attenuation factors of about 5000 : 1 were commonly found between subdural and scalp recordings; a 50 mV signal applied to two subdural electrodes 51 and 52 Fig. 4b, appeared on the scalp S_1 as a 10 μV signal.

DISCUSSION

From the foregoing experimental evidence it is clear that the appearance of scalp activity, be it spontaneous or evoked, is not dependent only on the *amplitude* of cortical activity, for even large cortical signals can be attenuated to such an extent as to be almost invisible on the scalp. On other occasions, however, low voltage cortical signals are observed on the scalp with little attenuation. It seems unreasonable to imagine that the impedance of the relatively passive tissue between cortex and scalp varies in such a manner as to have attenuation factors ranging from 2 : 1 (non-specific response) to 5000 : 1 (artificial generator). Other reasons must be sought to account for the evidence presented.

The largest attenuation factors observed in this study apply to those sources of electrical activity which occupy the smallest area of cortical surface (artificial generators and after-discharge) whereas the least attenuation factor (2 : 1) applies to the non-specific responses which are believed to involve large areas of cortical surface (Walter 1964).

Thus, although the amplitude of the cortical activity is obviously a factor in determining the amplitude of the scalp EEG, it is not the only one. Other factors, some of which may be more important than the cortical amplitude, include the cortical area involved and the degree of synchronisation of the electrical activity over this area. It is possible that the orientation of dipoles, if they exist in cortex, play a part in producing the various attenuations observed but since artificial dipoles parallel or perpendicular to the cortex are both grossly attenuated it seems unlikely that cortical dipole orientation can be a major factor.

The influence of area was studied by using a simple model. Recording electrodes were attached to the convex side of a large piece of fresh wet skull and a thin piece of polythene was placed in contact with the other side so that it covered most of the concave surface. Two large pads of cotton wool soaked in saline were placed on the polythene sheet 3 cm apart and connected to a low frequency, low impedance oscillator. The insulation of the plastic sheet was sufficient to prevent any field being picked up by the recording electrodes. Two pin holes were then punched in the polythene sheet one under each pad of saline, thus forming a generator with poles 3 cm apart. The field due to this generator was measured, using the recording electrodes, and the attenuation calculated. The effective area of the generator electrodes was increased by punching more holes in the polythene sheet under each saline pad. The attenuation factor decreased from 20,000 : 1 when the generator was two pin holes to 400 : 1 when 12 pin holes spread over 1 sq.cm were used for each pole of the generator. Attenuation factors of the same order as those observed in non-specific regions of frontal cortex could only be achieved by using generator electrodes greater than 1 inch square (2.5 cm $\times$ 2.5 cm).

Although this simulated EEG is not strictly comparable with the brain activity the results indicate that signals can be recorded from the scalp when large areas of cortical tissue are involved in synchronous or near synchronous activity of normal cortical amplitude. Alternatively, scalp activity, *although very small*, can be observed if small areas of tissue are discharging at very high voltage, as in after-discharge conditions.

In applying these conclusions to clinical problems the simplest case is the classical generalised wave and spike discharge. The very high voltage of this feature is adequately accounted for by its great extension; the area of cortex involved in synchronous discharge is so large that the cortical potential differences need be only about twice those observed on the scalp (about 1 mV). These would be similar in amplitude to those of the localised after-discharges evoked by electrical stimulation, which have a similar waveform. The high attenuation of the after-discharges is due to the small cortical area involved compared with the area involved in paroxysmal discharges of petit mal.

The small attenuation factor (3 : 1) of some of the alpha activity shown in Fig. 5 is explained in the same way, by assuming that the area of cortex involved in alpha activity at *A* is large, whereas at *B* it is small. This assumption is supported by the widespread alpha activity observed in the cortical and subcortical regions at *A* (channels 1, 5, 6, 7) whereas at *B* the amplitude of the cortical and subcortical activity is much smaller and more varied. The characteristic fluctuations in normal alpha rhythms are probably due mainly to changes in the area involved in synchronous discharge rather than to variations in local amplitude.

The widespread after-discharge shown in Fig. 6 is attenuated less because of the large areas of cortex involved. Even in this case, however, if only scalp recordings such as Ch.7 were available during the cortical events shown in Fig. 6, it would be difficult to attach much significance to the little transients seen. This emphasises again one of the main points of this study; the scalp EEG is a very poor indicator of the complex local activity going on at cortical level.

Although it appears that cortical areas of at least several centimetres square must be involved before scalp activity is observed when using normal EEG recording gains, not all of the cortical elements need be involved in the coherent activity. There is evidence that the cortical zones responsible for the non-specific responses are "patchy"; only a small fraction of cortical cells in any one area are involved in this activity. Scalp recordings will still be obtained with little loss of response amplitude provided the sum of the areas involved is about 6 sq cm and the coherent regions are close together.

As we have seen, the presence of a scalp EEG is dependent upon *synchronous* or near synchronous activity over a relatively large area of cortex; this means that small time differences between the occurrences of similar waves in neighbouring cortical regions will reduce the amplitude of the

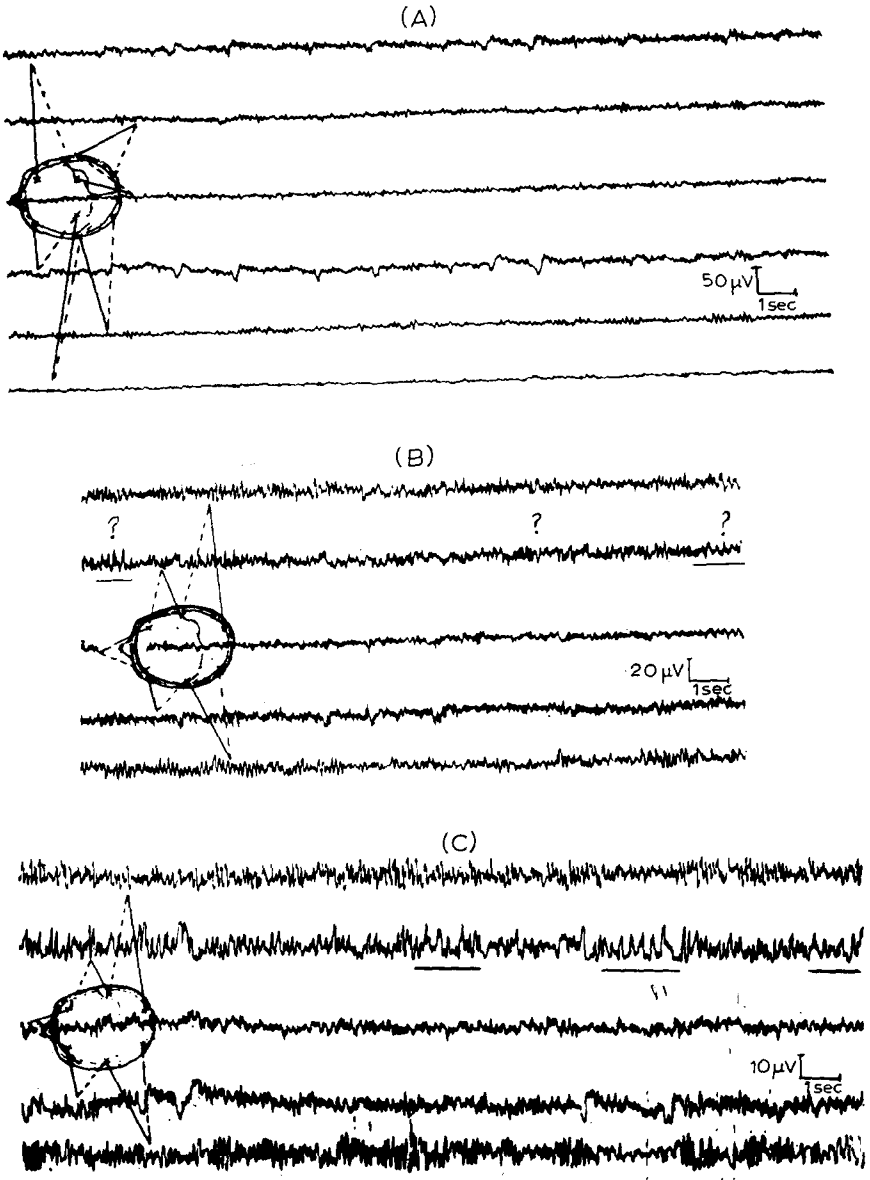

Fig. 9

Abnormal activity revealed by using greater EEG machine amplification.

A. Routine record, 50 μV/cm, no obvious abnormality.

B. Twofold increase in gain. Some abnormality (?).

C. Further twofold increase in gain, showing abnormal right frontal activity: gain 12.5 μV/cm.

scalp EEG. Furthermore, a given time difference of occurrence of waves will have a much greater cancelling effect on higher frequency activity than on low frequency activity. This is the reason why most of the frontal beta activity observed when using intracranial electrodes is invisible on the scalp. Special procedures such as injection of Pentothal may not cause new high frequency activity to appear but rather, *synchronise* the cortical areas already involved in beta activity. The inverse correlation between frequency and amplitude of scalp EEG rhythms may be explained in the same way as a vectorial function of extension.

From the point of view of interpretation of the scalp EEG the most important result of these studies is that with working gains of 50 μV/cm, and using electrode spacing as in the 10–20 system, the distinctive features of the EEG must represent coherent activity over quite large areas of cortex.

At lower working gains (100 μV/cm) the amplitude of coherent cortical activity must be much greater than usual or the area involved must be proportionately larger for a scalp EEG to be observed at all. One thing can be concluded; in a department using gain settings of 100 μV/cm and standard 10–20 system electrode placement, any "abnormal" EEG activity observed on the scalp must represent a very gross disturbance of cortical function. In these operating conditions much information of cortical activity is lost and, although the study of high gain records (25 μV/cm or higher) will present problems, it is suggested that at least part of routine recordings should be taken at these settings. With practice it will be possible to interpret the new information of localised high voltage or widespread low voltage cortical activity and correlate these data with clinical conditions.

Information which can be revealed by increasing the amplifier gain is demonstrated by Fig. 9. The three sections are taken from the same record. Part *A* was taken at a gain of 50 μV/cm, which is higher than that usual in some departments, and showed no obvious abnormality. Some evidence of slow activity was seen when the gain was increased twofold (*B*) but only when the gain was increased to 12.5 μV/cm was clear evidence obtained of right frontal slow activity. Neurosurgical investigation revealed a right frontal astrocytoma.

Such high-gain recordings demand a higher standard of technique, especially in the preparation of electrodes and maintenance of amplifiers. Non-linear elements may have to be introduced to prevent overloading by the activity of large cortical areas but it is felt that such difficulties are small compared with the benefits which may be obtained, both in clinical application and in the understanding of normal brain mechanisms.

SUMMARY

1. Intracerebral recordings show that there is little field spread (volume conduction) in brain tissue and that cerebral models with dipoles deep within the brain are not satisfactory.

2. Comparison of subdural and scalp recordings shows that only widely synchronised components of the cortical activity are observed on the scalp.

3. For strictly localised activity the attenuation from cortex to scalp can be as high as 5000 : 1, but for coherent activity over a wide area it may be only 2 : 1.

4. Model experiments indicate that cortical areas of at least 6 sq cm must be involved in synchronous or near synchronous activity before the scalp EEG is observed, using standard working gains.

5. A plea is made for higher working gains for part of routine EEG recordings.

RÉSUMÉ

COMPARAISON DE L'ACTIVITÉ DÉRIVÉE DU SCALP AVEC CELLE ENREGISTRÉE PAR ÉLECTRODES À DEMEURE CORTICALES ET SOUS-CORTICALES

1. Les enregistrements sous-corticaux montrent que le champ électrique ne se répand que très peu dans le tissu cérébral, et que les modèles cérébraux à dipoles profonds sont peu satisfaisants.

2. Une comparaison des enregistrements corticaux avec ceux du scalp indique que les composantes les plus largement synchronisées seulement se révèlent sur le scalp.

3. Pour l'activité strictement localisée l'atténuation entre l'écorce et le scalp peut être 5000 : 1, mais pour l'activité largement cohérente elle se réduit jusqu'à 2 : 1.

4. Les expériences avec des modèles indiquent qu'employant des gains courants l'EEG n'apparaît sur le scalp que si une aire corticale d'au moins 2.5 × 2.5 cm se trouve engagée dans l'activité synchrone.

5. Nous suggérons qu'une partie de l'enregistrement courant soit effectuée avec un gain élevé.

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