Current trends in electroencephalography
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Several recent articles re-emphasize the value of clinical electrophysiology: in localizing epileptogenesis, predicting effectiveness of epilepsy surgery, and disclosing a mechanism of benign Rolandic epilepsy of childhood.

A review of the role of EEG in the diagnosis of epilepsy indicated that epileptiform activity will appear in 50% of initial awake recordings of adults with epilepsy and in 85% of subjects undergoing two recordings. This contrasts with the appearance of spikes in only 4 of 1000 normal persons. Several studies focused on the value of electroencephalography in extratemporal epilepsy: 62% of patients with neocortical epilepsy had at least one localizing ictal EEG; occipital and temporal neocortical seizures were localized in a greater proportion than frontal or parietal attacks. Interictal spikes, if unifocal, always arose from the epileptogenic region in a study of their seizure localizing value. Such congruence augured for better seizure control by focal resection in two studies reviewed herein.

Studies indicating the value of interictal temporal lobe spikes and scalp-recorded seizures in localising a temporal seizure focus are reviewed. One study found EEG to be slightly more reliable for localisation of interictal temporal epileptogenesis than MRI. In patients with benign Rolandic seizures, enhanced motor evoked potentials (MEPs) were obtained from transcranial magnetic stimulation when this was applied 50–80 msec after electrical stimulation of the thumb whereas this interval inhibited the MEP in normal subjects. This suggests that afferent cutaneous input abnormally and synchronously activates a large population of sensory neurons; such activation is subsequently transmitted to the motor cortex to produce the focal spikes in this condition.

Finally, advances in non-invasive technology have redefined and limited the need for invasive monitoring in children with intractable seizure disorders. Curr Opin Neurol 14:193–197. © 2001 Lippincott Williams & Wilkins.

Introduction
Two current trends will continue to enhance and clarify the role of electroencephalography (EEG) in clinical neurophysiology. As EEG technology and statistical analysis become more sophisticated, the clinical relevance of traditional EEG becomes more defined. Moreover, newer electrophysiological methods promise to enhance further the value of traditional EEG. Some recent findings of these traditional and newer aspects of EEG form the subject of this concise overview.

Role of electroencephalography in the diagnosis and management of epilepsy
Binnie and Stefan [1•] reviewed the diagnostic sensitivity and specificity of EEG in epilepsy. Although interictal epileptiform activity is apparent in only approximately 50% of single awake recordings in adults with epilepsy, this proportion rises to 80–85% if sleep is included. Two awake recordings will demonstrate epileptiform activity eventually in 85% of individuals, and this rises to 92% of persons within four recordings.

These authors quoted studies that show that spikes occur in four of 1000 normal persons. More relevant, however, is the incidence of epileptiform activity in a patient population without a history of epilepsy. Ajmone Marsan and Zivin [2] found a 2–3% incidence, because some systemic or nonepileptic cerebral illnesses may be associated with spikes.

Binnie and Stefan [1•] pointed out that the clinician is often faced with an inadequate description of a clinical event, and relies on the EEG to determine its nature. Evidence-based data must be interpreted in this light; for example, Gilbert and Buncher [3] found EEG to have little value in predicting recurrence risk after a first unprovoked seizure in childhood. However, EEG has several other uses in relationship to epilepsy, as outlined by Binnie and Stefan [1•]. In addition to supporting the diagnosis of epilepsy, EEG may classify epileptic seizures into an epilepsy syndrome, it may monitor absences, it may recognize previously unidentified or misclassified attacks as seizures, and it may detect signs of antiepileptic drug intoxication.

Value of electroencephalography in extratemporal epilepsy
Lee et al. [4•] studied the localizing value of ictal surface EEG in neocortical epilepsy by analysing 394 ictal recordings from 86 neocortical epilepsy patients. All patients had neocortical epileptogenic foci, as confirmed
with presurgical invasive electrodes. Fifty-three of the patients (62%) had at least one localizing ictal EEG, and 167 localizing EEGs were identified in the 394 ictal recordings (42%). An additional 10% of patients and 9% of recordings gave lateralizing information whereas 49% of EEGs in 28% of the patients were unhelpful. Ictal EEG was of significantly less value in simple partial seizures, a finding that has been noted by others. Occipital lobe seizures and temporal neocortical seizures could be localized in a greater proportion than could frontal or parietal attacks with respect to both proportion of patients and of seizures (Table 1).

Holmes et al. [5] also found the scalp EEG to reflect ictal origin, but in a restricted percentage of patients. They reviewed 126 patients with refractory extratemporal partial seizures who underwent epilepsy surgery. In 26 (21%), interictal spikes were unifocal and in all cases clinical seizures arose from the interictal spike region. Follow up indicated that the most significant predictor of a seizure-free outcome after surgery was the presence of a discrete unilateral EEG spike focus. That study also found that the best outcome after surgery occurred when the ictal EEG origin was congruent with a magnetic resonance imaging (MRI) focal lesion. Of patients with this arrangement 43% became seizure-free and only 11% were less than 75% improved; when EEG and MRI data were less congruent, 48% were still seizure-free but 34% received less than a 75% improvement. Similarly, in paediatric patients, Paolicchi et al. [6] found that complete resection of not only the epileptogenic lesion, but also the electrographically abnormal region was the main determinant of outcome after focal resections.

Libenson et al. [7] found approximately the same clinical correlations of occipital epileptiform discharges in children as did Smith and Kellaway [8] in 1964! The majority of the group studied by Libenson et al. and that by Smith and Kellaway had seizures, but a substantial portion remained cryptogenic, with the others suffering various insults at early age; 40% of each group had generalized tonic-clonic attacks, whereas simple and complex partial attacks of varying descriptions constituted the remainder of the seizures in each group. A substantial proportion of each group had cognitive and/or behavioural abnormalities, and a significant minority had some type of visual impairment. Occipital foci tend to appear at early ages as indicated; relatively few patients in the group studied by Smith and Kellaway were older than 8 years, and spikes did not appear on subsequent recordings (age not indicated) in 38% of the patients studied by Libenson et al.

Electroencephalography and benign central temporal (Rolandic) epilepsy of childhood

Kellaway [9] described the morphological features of ‘Rolandic’ spikes and contrasted the topologically stationary and slightly propagating varieties. The predominant negative spike may be preceded by a low-amplitude sharper surface positive spike, and is preceded by a trough followed by an after-coming slow wave.

In an ingenious study, Manganotti and Zanette [10] utilized electrical stimulation of the fingers and motor-evoked potentials (MEPs) produced by transcranial magnetic stimulation to study the physiology of Rolandic spikes. Among patients with benign Rolandic epilepsy, somatosensory-evoked potentials elicited by stimulation of the fingers were of extremely high amplitude and appeared as an evoked Rolandic spike. Approximately 60% of electrical stimuli of the thumb evoked Rolandic spikes among such patients. Using electrical stimulation of the thumb as the conditioning stimulus and MEPs by transcranial magnetic stimulation as the conditioned stimulus, in control subjects prior electrical stimulation of the thumb inhibited the MEP at interstimulus (conditioning–conditioned) intervals of 50–80 ms, whereas the MEP in this interval was facilitated among patients with benign Rolandic epilepsy. The facilitating interstimulus intervals corresponded to the late part of the ascending phase and the peak of the evoked spike, but not to earlier and later components. The authors reasoned that afferent inputs from digital cutaneous territories drive a hypersynchronous activation of a large population of sensory neurones that are the anatomical source of the interictal spikes. A depolarizing event in the sensory area could produce a hypersynchronous neuronal discharge that is transmitted to motor cortex by cortical–cortical connections. This sequence would explain the enhancement of motor cortex output corresponding to the ascending phase and peak of the spike and not to the earlier, presumably sensory components. This study illustrates that valuable neurophysiological insights can be obtained by carefully designed and executed clinical investigation.

Electroencephalography in temporal lobe epilepsy

The value of the interictal spike in localizing temporal epileptogenesis has been increasingly recognized in recent years, as reviewed by So [11]. Blume et al. [12]...
found that most or all seizures arose ipsilaterally to the majority of temporal spikes in 99 out of 104 patients (95%); of those with greater than 3:1 side:side spike ratio, this proportion rose to 79 out of 80 patients. Focal unilateral temporal EEG delta activity also was correlated with seizure origin in over 90% of cases. Pataria et al. [13] found that, when temporal lobe spikes predominated on the same side of hippocampal atrophy, approximately 90% of recorded seizures arose ipsilaterally. The review of So [11\*] indicated that interictal discharges may also predict efficacy of anterior temporal lobectomy, in that congruency between temporal spike location and ictal onset was associated with excellent postoperative seizure control. A congruent MRI abnormality enhanced further the probability of an excellent surgical outcome to almost 95%. However, temporal spikes may not appear in approximately 10% of patients with intractable temporal epilepsy.

Further support of the value of interictal EEG is derived from a study by Cendes et al. [14]. Those investigators studied lateralization of temporal lobe interictal spikes, hippocampal atrophy on MRI and seizure lateralization in 184 consecutive patients with temporal lobe epilepsy who subsequently underwent effective temporal lobectomy. EEG was evaluated as seizure lateralization, MRI as interictal and ictal EEG lateralizations. Lateralization of hippocampal atrophy agreed closely with that of interictal and ictal EEG (Cohen κ 0.90), and all patients with unilateral hippocampal atrophy had concordant EEG lateralization. However, six out of 33 patients with bilateral asymmetrical hippocampal atrophy had discordant EEG lateralization.

Moset et al. [15\*] compared the usefulness of presurgical EEG, MRI and neuropsychological data in the lateralization of temporal lobe epilepsy in patients who subsequently underwent effective temporal lobectomy. EEG was evaluated as seizure lateralization, MRI as left–right differences in hippocampal volume, and neuropsychological data consisted of mean scores of five cognitive tests. EEG was slightly more reliable for lateralization than was MRI (89% versus 86%) and both were superior to neuropsychological data (66%) using these measures.

Taken together, data from these studies suggest that interictal temporal lobe spikes and recorded seizures each can lateralize the temporal seizure focus. If they are consistently lateralized to the temporal lobe that harbours unilateral hippocampal atrophy, or epileptogenic lesion, then in-patient monitoring could be obviated. Patients with scarce interictal spikes or bilaterally appearing indices of epileptogenesis may require in-patient investigation.

**Intracranial electroencephalography**

The aforementioned correlations represent some of the factors that have reduced the proportion of patients undergoing invasive electroencephalography. For example, only 21 out of 184 consecutive temporal lobe patients in the patients studied by Cendes et al. [14] underwent such recording.

Therefore, such investigation can be avoided when interictal and ictal scalp EEG, neuroimaging and neuropsychological testing favour one area of temporal epileptogenesis. As reviewed by Diehl and Luders [16], less congruency likely will require invasive recordings, i.e. when: (a) EEG monitoring and MRI findings are discrepant, (b) multifocal seizure onsets are suspected, and (c) the site of seizure onset cannot be localized by scalp EEG. In nontemporal epilepsy, invasive recordings are frequently required when epileptogenesis from a region distant to surface EEG electrodes is suspected, such as an inferior or mesial frontal or occipital surface [17].

Rapid advances in noninvasive technology have resulted in a reduced need for invasive monitoring in children also [18\*]. Jayakar [18\*] doubts that invasive monitoring is necessary when all noninvasive data reflect an epileptogenic region within the area of the planned resection or when intra-operative electrocorticography (EcoG) reveals almost continual focal discharges. Moreover, that investigator cautioned that limitations of sampling and interpretation still exist for invasive monitoring. He indicated the greatest benefit of invasive monitoring may be achieved among children who are neurodevelopmentally intact and who have a restricted epileptogenic zone, as defined by scalp EEG and imaging. Patients with clinical evidence of a diffuse encephalopathy or multifocal and diffuse epileptogenic patterns on scalp EEG and multifocal neuroimaging lesions are unlikely to benefit.

The group of Jayakar found invasive monitoring helpful when studies suggest epileptogenesis in the posterior temporal occipital region encroaching upon language cortex, and when distinction between anterior temporal and orbital frontal epilepsy is not clear. Finally, Jayakar [18\*] and others have noted that the epilepsy associated with an epileptogenic lesion is not homogeneous in its vicinity. The epileptogenic lesion can be larger or smaller than the lesion or may involve one of its boundaries preferentially [19].

**Electroencephalography and functional neuroimaging**

In addition to new studies using traditional methods for localizing epileptogenesis, functional imaging holds some promise for delineating epileptogenic areas. These may obviate the need for invasive recording in some
patients, whereas in others it may direct electrode placement to the most likely regions, saving the patient unnecessary implantation.

**Electroencephalography-linked functional magnetic resonance imaging (fMRI)**
Schomer et al. [20] described their findings from functional MRI acquisitions triggered by EEG spikes, having developed instrumentation that allows EEG within the MRI unit. The relationship between focal increases in neuronal firing rates, as reflected in the EEG spikes and provoked focal increases in blood flow, enabled those investigators to develop functional MRI-linked images that depict the origin of such activity.

**Magnetoencephalography**
As magnetic signals are far less distorted by intervening tissues than are electrical signals, magnetoencephalography (MEG) provides a better spatial resolution of signals than does conventional EEG [21]. MEG dipole modeling can noninvasively attribute spike activity to subcompartments in a temporal lobe, such as the mediodisal temporal lobe and the temporal tip cortex. Moreover, MEG spike dipoles can be localized adjacent to lesions that are visible on MRI scans [21]. Unfortunately, MEG requires the patient to remain in a single position throughout the recording, limiting its duration; ictal recordings are not yet practical. EEG can detect all MEG-recorded spikes, but some EEG spikes are missed by MEG [21]. The practical value of this approach for detecting epileptogenesis remains uncertain.

**Single-photon emission computed tomography (SPECT)**
As reviewed by So et al. [22*], interictal single-photon emission computed tomography still has low sensitivity (28–66% among various studies) and specificity in the detection of an epileptogenic area. However, longer half-lives of newer radiotracers have augmented the sensitivity of detecting ictal hyperperfusion to 90% for a temporal focus and to 81% for an extratemporal focus, and specificities are 77 and 93%, respectively [22*]. The group of So et al. [22*] superimposed the subtraction of interictal (hypoperfusion) from ictal (hyperperfusion) scans on MRI, and improved the sensitivity for detecting an epileptogenic focus to 88%. Because standard MRIs disclosed no lesion in half of these patients, such findings hold considerable promise for nonlesional frontal lobe intractable epilepsy.

**Positron emission tomography (PET)**
In addition to the traditional fluorodeoxyglucose, positron emission tomography (PET) may also detect altered benzodiazepine receptor function, specifically flumazenil imaging. Juhász et al. [23] found flumazenil PET to be more sensitive than fluorodeoxyglucose PET in detecting the area of seizure onset, as defined by invasive ictal EEG. Review of flumazenil PET by these authors found correct epileptogenesis localization in 57–100% of studies carried out from 1993 to 1998.

**Summary of functional imaging modalities**
Each of these methods help to localize epileptogenesis in circumstances that are occult to conventional means. In common with surface and invasive EEG, each has a sampling problem. Although these methods partially overcome the spatial sampling limitation of surface and invasive EEG, they fail to detect the chronology of the epileptic process in terms of origin and early propagation. Practical and economic considerations limit the duration of such monitoring. One or more of these relatively expensive methods may actually save money if invasive monitoring is avoided in some patients. However, only neurophysiological recordings will provide the critical temporal resolution for the investigation of seizure initiation and propagation in human epilepsy.

**Electroencephalography in coma**
‘The EEG is underused in coma’ [24]. Although clinical examination can assess brain-stem function in comatose patients, cortical activity is largely closed to clinical assessment. A wide spectrum of EEG findings may be seen in patients with a similar impairment of brain-stem function. As the variety, complexity and reactivity of EEG rhythms correlate inversely with the severity of cortical dysfunction, certain EEG patterns contribute to prognosis for survival. In particular, these involve EEG ‘suppression’ or lack of function, as well as lack of reactivity [25]. The presence of one of several characteristic EEG coma patterns may enable one to determine the general category of a disease process (i.e. metabolic, drug-induced, or structural). Continuous EEG monitoring is principally indicated in patients with an unstable or potentially treatable condition such as status epilepticus, recurrent seizures, and variable intracranial pressure or cerebral perfusion [24]. Because the treatment of refractory generalized convulsive seizures may involve pharmacological paralysis of motor function, electroencephalography is necessary to assess progress. Nonconvulsive status epilepticus may develop de novo or may evolve from convulsive status epilepticus. By performing routine EEGs on comatose patients, Towne et al. [26] found nonconvulsive status epilepticus in 8% of 236 patients with no overt clinical seizure activity. Age and aetiology did not distinguish patients with and without nonconvulsive status epilepticus. These authors found generalized, hemispheric, or bilateral independent persistent epileptiform activity.

**Conclusion**
Mysteries and complexities of central nervous system function and dysfunction are best unravelled by studies
and investigations combining methodologies. Therefore, it is gratifying to see in this age of prominent neuroimaging, that clinical electrophysiology retains its essential role.

References and recommended reading

Papers of particular interest, published within the annual period of review, have been highlighted as:

• of special interest
•• of outstanding interest

This review provides sensitivity and specificity data which could be used in positive predictive value studies.


This study indicates that surface EEG can identify epileptogenesis, particularly for occipital and temporal lobe epilepsy.

This study provides additional supportive data for the value of interictal EEG, the most common situation presented to the clinician.


This is a particularly carefully done, multi-modal neurophysiological study exploring the pathophysiology of the most common form of benign focal epilepsies of childhood. Its value lies in both the careful methodology and in the results.

This is a useful review comparing three methods of localizing epileptogenesis.


Their data also support the value of surface electroencephalography in lateralizing temporal lobe epilepsy, supporting the diminishing need for invasive electroencephalography.


Attention to principles elaborated by Jayakar will guide clinicians in selecting children most appropriate for invasive monitoring.


This communication describes Subtraction Ictal Single Photon Emission Computed Tomography Coregistered to Magnetic Resonance Imaging (SISCOM), a potentially useful technique in localizing epileptogenesis when MRI is normal.


