

## EEG MONITORING AND EVOKED POTENTIALS IN BRAIN ISCHAEMIA

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In 1875 Richard Caton observed electrical oscillations from the brains of animals which altered during dying and ceased with death. Similar alterations may follow cerebral circulatory arrest, exsanguination or inadequate cardiac action. The EEG fails within 20 s of cessation of the circulation and can recover within 30 s of its return, but there is a longer latency to return of EEG if ischaemia is more than momentary. The decline of the EEG was considered to be characterized by a decrease in the faster waves and an increase in the slower ones leading to electrical silence, with a reversal of this sequence during recovery (fig. 1). However, with abrupt onset of ischaemia rapid transition from a continuous “activated” EEG to a burst suppression pattern and silence is more often observed (Brierley et al., 1978). The EEG changes and their time course are comparable in both localized and global ischaemia, and similar but totally reversible depression is also found when brain metabolism is depressed by narcosis or profound hypothermia (Prior, 1973).

### METABOLIC BASIS OF CEREBRAL ELECTRICAL ACTIVITY AND EFFECTS OF ISCHAEMIA

The EEG is a summation of volume-conducted potential fields from postsynaptic potentials of myriads of neurones, mainly of pyramidal type in the ganglionic layer 5 of the cerebral cortex. Neurones exhibit a resting potential difference of  $-70$  mV across their membranes, maintained by ionic transport by the sodium–potassium pump. Propagation of impulses along axons is accomplished by depolarization (reduction) of the membrane potential, a threshold of  $-50$  mV being sufficient to trigger the all-or-none action potential

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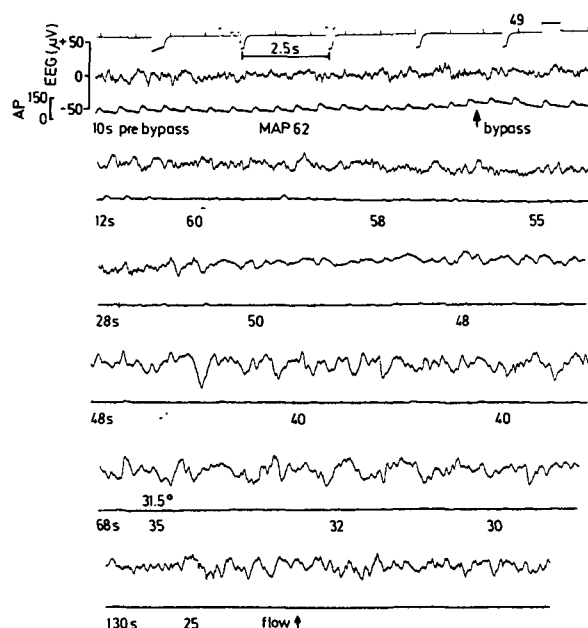


FIG. 1. EEG alterations at onset of cardiopulmonary by-pass: simultaneous EEG and radial artery pressure (AP) recording in a 22-year-old woman undergoing pulmonary valvotomy and infundibular resection. Full flow  $3.83 \text{ litre min}^{-1} \text{ m}^{-2}$  increased to  $4.70 \text{ litre min}^{-1} \text{ m}^{-2}$  later. Biparietal electrode placement. Mean arterial pressures (mm Hg) indicated.

which reaches approximately  $+30$  mV. Following chemical transmission across the synapses, postsynaptic potentials are triggered. These are of lower voltage than the action potential and are either excitatory (depolarizing) or inhibitory (hyperpolarizing). Simultaneous recordings from single neurones and of surface EEG demonstrate that trains of these underlying excitatory and inhibitory postsynaptic changes, rather than the action potentials, relate to the negative and positive waves of the EEG (Brazier, 1968; Eccles, 1968; Schmidt, 1978).

Potentials evoked by sensory stimuli are transmitted from the receptor organs and along peripheral neural pathways to the appropriate area of cortex. There the primary response recorded by large electrodes is an integration of local postsynaptic potentials of a great number of cortical neurones. The substantial energy utilized, even in the resting state, by all these processes is derived from the phosphate bond of adenosine triphosphate (ATP) produced by oxidative metabolism of glucose by mitochondrial respiration. The ATP is used both for ion transport and synthesis of transmitter substances.

Cerebral circulatory insufficiency or arrest (whether from cardiovascular inadequacy or from impairment of cerebral perfusion by increased intracranial pressure) prevents delivery of adequate oxygen and glucose to the brain. Cerebral oxidative metabolism decreases, whilst the high energy compounds phosphocreatine and ATP are rapidly exhausted and not replenished. Anaerobic glycolysis is a poor source of ATP and leads to lactate production. ATP may then be insufficient to maintain neuronal resting potentials essential for integrated brain function and its by-product, the electrical activity recorded in the EEG. When cerebral metabolic demands are high, for example during hyperthermia or seizures, reduced energy supply is necessarily more likely to lead to ischaemic damage. With resuscitative measures, normal energy metabolism may be restored but, none the less, functional neurological deficit can be catastrophic—probably at least in part from damage to transmitters and deranged amino acid metabolism. Irreversible cellular lesions occur when the neuronal membranes and those of their internal organelles are damaged beyond repair, by whatever mechanism (Nilsson, Norberg and Siesjö, 1975; Siesjö, 1978; Raichle, 1983).

#### *Thresholds for ischaemic depression of EEG and evoked potentials and for brain damage*

Three ischaemic thresholds require consideration: onset of abnormalities in electrical activity, its extinction and irreversible cell damage. Whilst the first two (which can be recognized by non-invasive monitoring) are simply reflections of cerebral blood flow (CBF) and oxygen delivery in relation to metabolic needs (at least in the normal brain), the third adds a factor of time.

Cerebral blood flow thresholds for depression of electrical activity and for brain damage have been established with models of focal ischaemia, typically

middle cerebral artery occlusion. Electrical abnormality occurs at regional cortical flow values of approximately  $20 \text{ ml min}^{-1}/100 \text{ g}$ , followed by extinction of spontaneous EEG and evoked potentials at approximately  $15 \text{ ml min}^{-1}/100 \text{ g}$  (Astrup et al., 1977; Morawetz et al., 1979). Single neurones show cessation of spontaneous electrical activity at a mean of 18 (range 6–22)  $\text{ml min}^{-1}/100 \text{ g}$ . If flows of  $14 \text{ ml min}^{-1}/100 \text{ g}$  or less persist for more than 45 min, their activity will not return with re-perfusion, and histology reveals selective neuronal necrosis (Heiss and Rosner, 1983). There is evidence that reversible neurological deficit occurs in the awake subject at slightly higher values—approximately  $23 \text{ ml min}^{-1}/100 \text{ g}$  (Jones et al., 1981) and that evoked potentials persist to slightly smaller values of CBF than spontaneous EEG (Shapiro, 1978). Permanent neurological deficit and infarction in the middle cerebral artery territory are described when flows of  $12 \text{ ml min}^{-1}/100 \text{ g}$  are sustained for 2–3 h (Jones et al., 1981), massive release of  $\text{K}^+$  ions being observed with flows in the region of  $6 \text{ ml min}^{-1}/100 \text{ g}$  (Astrup et al., 1977).

With global brain ischaemia, additional factors require consideration. Autoregulation of CBF usually fails at values of mean arterial pressure (MAP) less than 60–70 mm Hg (Lassen, 1959) and then CBF is pressure passive. In hypertensive animals autoregulation fails at higher pressures (Fitch et al., 1978). The lower limit for autoregulation may be as high as  $113 \pm 17 \text{ mm Hg}$  in hypertensive patients with resting MAP within the range  $145 \pm 17 \text{ mm Hg}$ ; however, with prolonged effective antihypertensive treatment, there is some evidence of readaptation towards normal (Strandgaard et al., 1973; Strandgaard, 1976). An added complication is that, in damaged brains, the usual interrelationships between CBF, metabolism and electrical activity may not obtain (Paulson and Sharbrough, 1974).

Thresholds for brain damage following global ischaemia are defined by a critical combination of reduced blood flow leading to electrical silence and time. Thus, in the Rhesus monkey, acute profound arterial hypotension had to be sustained for at least 15 min with cerebral perfusion pressures (CPP) of less than 25 mm Hg and EEG and evoked potential silence, to produce even restricted damage (Brierley et al., 1969; Meldrum and Brierley, 1969). Longer periods led to more extensive ischaemic necrosis. With less abrupt but progressive hypotension induced over 2–3 h in the cat, CBF became pressure-dependent at MAP values less than approximately

65 mm Hg and electrical abnormalities began at 30–40 mm Hg, with EEG and evoked potential silence occurring between 10 and 30 mm Hg. Infarction occurred when MAP was held at 25 mm Hg (and in one instance at 35 mm Hg), with comparable reduction in CBF to 8–11 ml min<sup>-1</sup>/100 g, for 20 min (Graham et al., 1979; Gregory et al., 1979; Mackenzie et al., 1979).

It is difficult to compare the many models of brain ischaemia because of widely differing methods and rates of producing ischaemia (some without parallel in clinical experience in man). Species differences are evident, partly from variations in cerebral vascular anatomy and physiology. Variations in normal ranges for MAP, different depths of anaesthesia, use of artificial ventilation and muscle relaxants, in addition to widely variable definitions of “recovery” also prejudice comparisons. Moreover, in almost every study reported, there are wide individual variations in CBF and CPP values for onset of electrical abnormalities and for infarction, even though mean values show consistent trends.

#### *Distribution and electrical correlates of ischaemic brain damage*

The end result of ischaemic stress to neurones is an alteration in cellular morphology, “ischaemic cell change”, which evolves over several hours. Complete circulatory arrest produces selective necrosis of vulnerable neurones in a characteristic distribution within the brain (Brierley, 1976). The widespread electrical abnormalities and their evolution allow prediction of the severity of brain damage (Lindgren, Petersen and Zwetnow, 1968; Brierley et al., 1971; Prior, 1973). When there is a rapid and considerable reduction in cerebral perfusion pressure, but not total cerebral circulatory arrest, ischaemic brain damage occurs along the boundary zones between the territories of the main cerebral arteries (Adams et al., 1966; Brierley et al., 1969). This pattern of damage is common to a wide variety of clinical conditions, including profound arterial hypotension and increased intracranial pressure (Graham, 1977). The earliest EEG alterations are found in the boundary zones, before the cortex in the middle of the artery territory is affected. The extent of the infarction is proportional to the severity and duration of the EEG depression during the insult and the early recovery period (Brierley et al., 1980; Malone, Prior and Scholtz, 1981).

The arterial boundary zone distribution of brain damage and of the earliest electrical abnormalities suggests that these are the optimal sites for monitor-

ing electrodes in global ischaemia. In contrast, electrodes should be placed over the main artery territory at risk when carotid artery or an intracranial artery occlusion reduces flow locally and collateral circulation is insufficient. If the ischaemic stress is primarily subcortical, the use of somatosensory evoked potentials rather than EEG monitoring should be considered (Hume and Cant, 1978; Symon et al., 1979).

#### METHODS FOR WARNING OF BRAIN ISCHAEMIA

Prevention of brain ischaemia depends upon reliable evidence of its imminence. Prevention of permanent ischaemic brain damage depends upon taking corrective action immediately warning signs appear. In man, ischaemia and brain damage occur at thresholds that vary between different individuals and clinical circumstances (table I). They are often multifactorial, even if not overtly so. Thus, ischaemia may lead to fits and a higher cerebral metabolic demand for oxygen but poorer oxygen delivery, all combining to increase damage. A critical combination of adverse factors may be unexpected and unrecognized in an individual unconscious patient. Some factors such as extra- or intracranial vascular disease, impaired autoregulatory capacity and cerebral metabolic requirements at a given temperature or anaesthetic depth, may not even be known. Routine clinical monitoring of ECG, arterial pressure and blood-gas tensions only indicates the adequacy of factors supporting brain function. The EEG and evoked potentials are more valuable because they can monitor continuously the end result at a neuronal functional level. If taken in the context of the supportive factors, contributory causes of ischaemic depression can be identified and the effect of appropriate treatment monitored.

#### *EEG and evoked potential recording*

The general principles for neurophysiological recording are detailed in a number of standard works. For EEG methodology, Tyner, Knott and Mayor (1983), Cooper, Osselton and Shaw (1980) and Binnie, Rowan and Gutter (1982), taken sequentially, address readers of progressively increasing sophistication. For evoked potential recording, Chiappa (1983) and Halliday (1983) provide superbly clear and comprehensive accounts of methodology and applications.

Neurophysiological monitoring requires impeccable electrode contact with the patient and avoidance of interference from unwanted signals. Specific

methods for recording EEG and evoked potentials in the operating theatre and the intensive care unit have been described elsewhere (Prior, 1973, 1979; Greenberg, Mayer et al., 1977; Greenberg, Becker et al., 1977; Hume and Cant, 1978; Raudzens, 1982; Goff et al., 1983; Grundy, 1983). Success depends upon attention to a number of practical points:

(1) *Choose the best electrodes.* Sterile intradermal needle EEG electrodes made of platinum-iridium alloy are used for quick access with least disturbance to the patient. For longer recordings silver-silver chloride EEG disc electrodes fixed to the scalp with collodion and filled with conductive jelly are required. Leads should be fixed securely with both. For recording at craniotomy, special electrodes are made usually of fine wires carried in light-weight plastic sheeting.

(2) *Measure the electrode contact impedance* and monitor it throughout if possible. It should be less than 5 and usually 1–2 k $\Omega$ ; if higher there will be more interference.

(3) *Use appropriate recording and reference electrode sites.* For EEG, bilateral fronto-centro-parietal or bi-parietal derivations cover the middle cerebral artery territories and the main arterial boundary zones, whilst avoiding sources of unwanted signals such as eye or jaw movements. When applying electrodes to the back of the head or neck, avoid undue neck flexion which can increase intracranial pressure by venous obstruction.

(4) *Record from more than one area if possible.* It is important to balance the need for simplicity against that for adequate information. Whilst a bi-parietal derivation may be quite adequate for general surveillance, warning of focal ischaemia would be provided better by appropriate regional placement of recording electrodes to enable comparison with contralateral homologous areas. Spare electrodes, placed before surgery, allow for unobtrusive substitution in the event of faults developing.

(5) *Have the pre-amplifiers near to the patient's head.* Transmitting amplified signals rather than those of a few microvolts, reduces the effect of interference.

(6) *Ensure patient safety.* Take account of modern recommendations and make regular safety checks. Conventional isolation amplifiers, opto-kinetic couplers or infra-red technology separate the patient from dangerous voltages. Avoid multiple mains leads or multiple earths and ensure that apparatus is safe during surgical diathermy or defibrillation.

(7) *Use special filters or circuits to minimize interference.* These include input isolation, notched filters

set at mains frequency (50 or 60 Hz) and radio frequency traps which may allow continuous recording to continue during surgical diathermy (Van der Weide and Pronk, 1979) or to be cut out to avoid blocking or damage to the apparatus. Equipment for evoked potential averaging normally incorporates rejection systems (e.g. on the principle of Schmitt triggers) which prevent acceptance of high voltage potentials which are likely to be artefactual.

(8) *Obtain sufficient baseline or normative data* before the time of risk so that effects of anaesthesia, sedation or hypothermia can be assessed. This may also imply monitoring the EEG during recordings of cerebral evoked potentials so that any depression from anaesthesia is not mistaken for ischaemia. If techniques are standardized as much as possible, unusual features or abnormalities will be noticed more easily. Technicians must have adequate training and equipment to be capable of flexibility.

(9) *Do not treat neurophysiological data in isolation.* Most alterations are non-specific and can only be interpreted sensibly in context. Polygraphic recording of EEG with other physiological variables on a single well annotated chart, avoids many ambiguities.

(10) *Use appropriate processing and displays to reduce and clarify the data.* Special methods are virtually obligatory for long periods of EEG monitoring, because of the complexity and bulk of the traditional multichannel chart recordings and the inherent difficulties in recognizing trends and providing quantification.

#### *EEG analysis and display*

The EEG can be described or quantified by various methods (Handbook 1972, 1973; Rémond, 1977). The inherent tendency of slow waves to be of higher amplitude than faster ones (figs 1 and 2) requires that EEG monitoring systems may need compensatory pre-filtering. Data reduction then takes one or both of two general forms: (1) continuous measurement of amplitude by integration or amplitude variability envelope. These are designated time domain analyses, in that the chosen variable is plotted against time, for example as in the cerebral function monitor (CFM) (Maynard, Prior and Scott, 1969) (fig. 2). (2) Frequency analysis, usually as an average over seconds or even minutes and derived from tuned filters or fast Fourier and related transforms. These are designated frequency domain analyses, in that a chosen measure such as EEG power is plotted against frequency. Wave

period analysis and baseline (zero) crossing counts, although essentially time domain methods, are often displayed to give a pseudo-frequency domain effect. In general, being based on averages over chosen epochs of time, frequency domain analysis has inherent disadvantages for monitoring. It assumes that the EEG is stationary, it masks events that are short-lived or atypical with respect to the whole epoch, and it cannot indicate the variability of the signal, except from sequential or overlapped epochs.

Displays of processed EEG take many forms. The simplest are the single line representing continuously integrated or envelopes of amplitude. Frequency data may be reduced to a mean (which can lead to ambiguity and conceal significant events such as burst suppression activity or near electrical silence) or displayed as ratios (equally risky) or as detailed power spectra by a series of histograms. Smoothing and sequential presentation result in the compressed spectral array (CSA) (Bickford et al., 1973) or grey scale dot formation density modulated array (DSA) (Fleming and Smith, 1979). The new generation of monitors display combined time and frequency domain data such as wave period and amplitude (Klein and Davis, 1981), CSA with integrated amplitude (Myers, Stockard and Saidman, 1977; Pronk, 1982) or the modified CFM (CFAM) (Maynard, 1977; Maynard and Jenkinson, 1984) (fig. 3).

Critical comparisons of various monitoring methods regarding their performance in detecting

ischaemia change are few and often disappointingly inadequate. Several aspects have to be considered, such as efficiency in demonstrating relevant abnormality, ability to respond quickly to ischaemic change but not excessively to fluctuations in level of consciousness or with artefactual interference (Matoušek, Arvidsson and Friberg, 1978). In focal ischaemia, CBF has been correlated with mean EEG frequency quantified by various methods (Tolonen and Sulg, 1981). In patients undergoing carotid endarterectomy, Chiappa, Burke and Young (1979) found that analysis by minicomputer (CSA combined with integrated amplitude from each hemisphere plus asymmetry detection) invariably rendered the EEG change more apparent than did conventional recording. Significantly, these authors noted that their 4-s CSA epoch so "smoothed" the trace that the burst-suppression pattern from fast-acting barbiturates was not evident, an observation also noted by Levy (1984) in cardiac surgery. Further, the only EEG parameter significantly associated with damage after operation was amplitude depression.

There have been two extensive comparative studies for intraoperative monitoring during possible global ischaemia. In cardiac surgery, Pronk (1982) and Pronk and Simons (1982) found that each of the five major types of analysis tested in 30 patients was very effective, but they concluded that a combined frequency (zero cross) and amplitude (integration) display gave greatest safety. They indi-

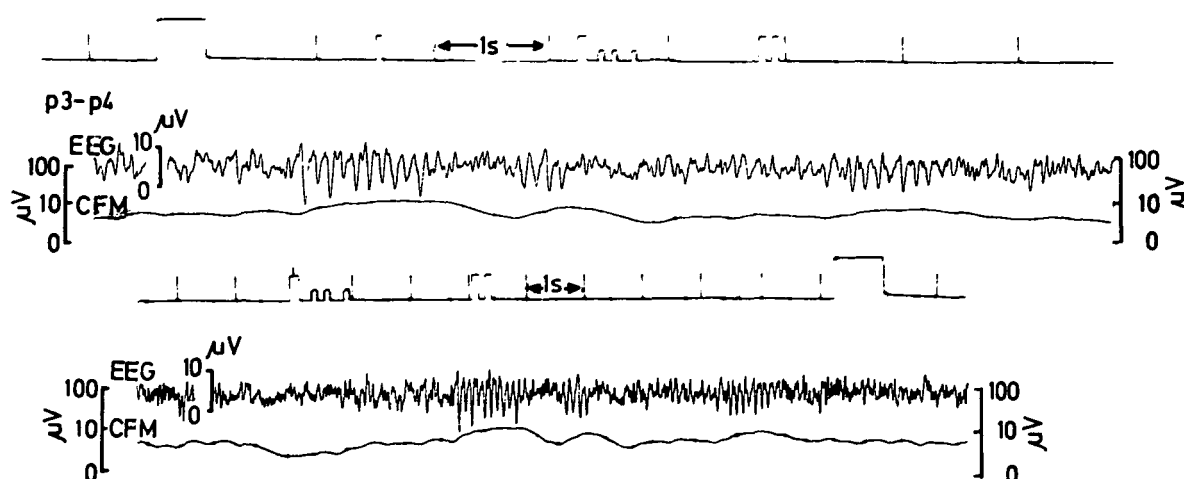


FIG. 2. Simultaneous recording of EEG and cerebral function monitor (CFM) from left and right parietal electrodes in a normal subject, awake with the eyes closed. The same data are presented at two different chart speeds to show how the increased peak-to-peak amplitude ( $\mu\text{V}$ ) of a burst of alpha waves results in an increase in amplitude of the CFM trace. CFM amplitude fluctuates with the amplitude envelope of the raw EEG.

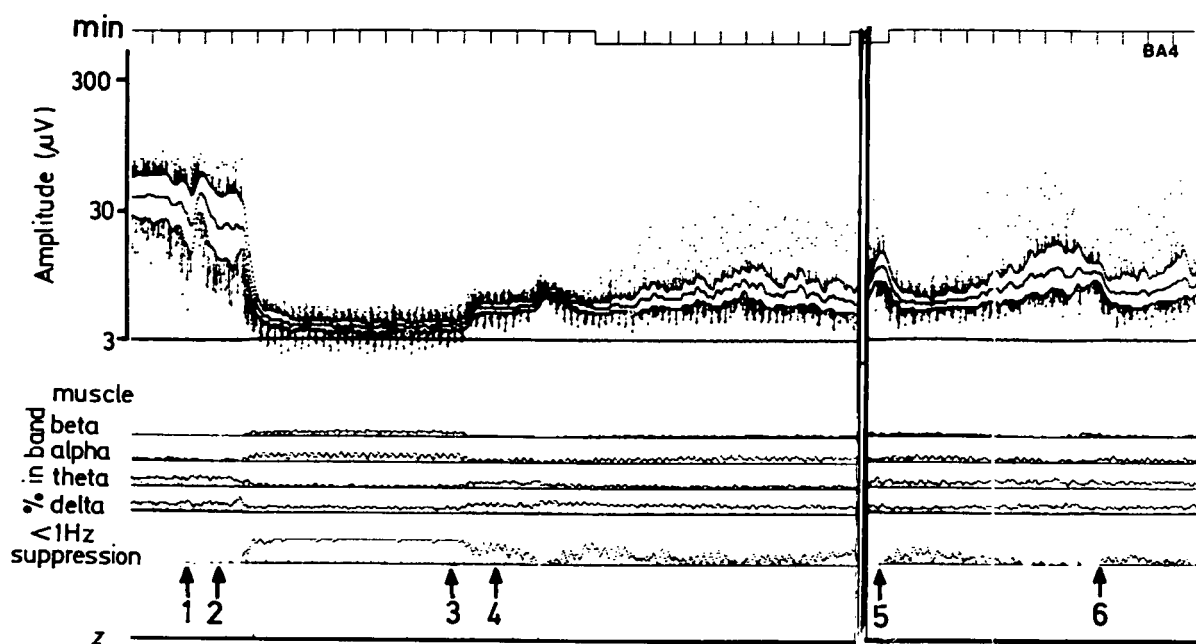


FIG. 3. CFAM recording during combined hypoxia and ischaemia: the CFAM has a passband of 1–27 Hz and a fully logarithmic scale. Amplitude (calibrated peak-to-peak at 10 Hz) is given as backwards weighted mean values updated every 2 s for mean voltage, 90th and 10th centile values and peaks and troughs exceeding these. Frequency analysis is given as the percentage of power falling into the traditional EEG frequency bands (beta, alpha, theta, delta) and also activity of less than 1 Hz and periods of suppression below a preset voltage limit. Muscle potentials and electrode impedance ( $z$ ) can also be indicated. This recording is from left centroparietal extradural electrodes in a spontaneously breathing baboon anaesthetized with Althesin infusion  $0.42 \text{ ml kg}^{-1} \text{ h}^{-1}$ ,  $P_{aO_2}$  3.99 kPa and right common carotid occlusion (Brierley et al., 1980). At (1) left common carotid occlusion, mean arterial pressure (MAP) increased from 131 to 163 mm Hg, (2) trimetaphan  $38 \text{ } \mu\text{g}$ , MAP decreased to 48 mm Hg and vertebral Doppler pulse became undetectable, (3) carotid clasps removed and (4) metaraminol restores MAP to 143 mm Hg and Doppler pulse returns. Subsequent myoclonic jerks and opisthotonic spasms controlled by additional bolus doses of Althesin 0.2 ml at (5) and (6).

cated that choice of methods could reasonably be made on grounds of cost and simplicity, factors also discussed by Levy and others (1980). Comparisons are also available between 28 spectral EEG parameters and 14 CFAM measures (fig. 3) from 33 patients during controlled hypotension or cardiopulmonary bypass (Matoušek et al., 1985). Most significant alterations with onset of ischaemic stress concerned amplitude rather than frequency content. Features most highly correlated with decreasing arterial pressure were mean amplitude from the CFM or CFAM and amplitudes of delta, upper alpha and lower beta bands or summed amplitudes from spectral analysis. However, frequent disturbance of the delta band by artefact during surgery entails that amplitude in the 10–17 Hz range is of greater interest for monitoring, and it can be derived from simple analog filtering. This also allows clear display of burst-suppression

activity or electrical silence. The multimodal character of EEG changes at onset of bypass has been emphasized by Levy (1984), who demonstrated in 30 patients that neither mean frequency nor spectral edge frequency reflected their complexity, and he concluded that univariate descriptors were inadequate for monitoring the EEG changes in a large percentage of patients.

#### *Specification for EEG monitoring systems*

It is evident from these reports that many EEG measures are sensitive to changes induced by ischaemia and practical differences between monitors relate much more to cost, susceptibility to artefact, ease of use and of measurement, and interpretation of displays. Interestingly, no study appears to have addressed the psychology of communicating information by such monitors in operat-

ing theatres and intensive care units. Monitors should be powerful in separating different, in addition to classifying similar, EEG patterns, be easy to interpret in clinical and EEG terms, be theoretically well founded, numerically stable, and robust even in the presence of small deviations from the model on which the analysis method is based (Matthis, Scheffner and Benninger, 1981). Operation should be automatic without need for gain adjustments; signals likely to be artefactual should be rejected automatically. Clear time-coding and warnings of high electrode impedance and interference should be given. In order to detect ischaemia, low voltage activity must be emphasized: conditions where cerebral metabolic demands are high, such as seizure discharges or responses to pain, must also be recognizable. Time domain (e.g. period-amplitude) analyses are well suited to the purpose, generally easy to learn to read and, if filters exclude slow waves, are not affected by artefacts. They are less disturbed by changing depth of anaesthesia than frequency ratios and more informative than mean values. Modern monitors will provide a combination of amplitude and frequency distribution information to give early warning of brain ischaemia. Ideally, these features should be in a compact apparatus which also has facilities for display of other physiological variables and evoked potentials.

#### Evoked potential analysis and display

When a sensory stimulus occurs, potentials are elicited at the receptor site and then travel via neural pathways to the appropriate central relay nuclei and primary cortical representation areas. The evoked spinal, brainstem and cerebral potentials individually are of relatively low voltage and may well be unrecognizable amongst other concurrent higher amplitude activity. However, averaging sequentially from the time of each of a train of stimuli enhances any time-locked potentials ("signals") at the expense of unrelated "noise". Small averaging computers are used to control stimulus delivery and process and display the averaged sensory evoked potentials. Appropriate evoked potentials (fig. 4) in patients at risk of brain ischaemia include *brainstem auditory evoked potentials (BAEP)*, a series of five waves occurring within about 6 ms of a sound. The latency difference between the first and fifth waves indicates transmission time through auditory nerve and brainstem. *Somatosensory evoked potentials (SSEP)*, from electrical stimulation of peripheral nerves, can be recorded over spinal cord and at

somatosensory cerebral cortex about 20 ms after stimulation at the wrist (Mauguière, Desmedt and Courjon, 1983). The difference in latency between cortical and upper cervical spine potentials, designated the central somato-sensory conduction time (CCT) (Hume and Cant, 1978) is about 5 ms. *Visual evoked potentials (VEP)* to flash stimulation have some place in the detection of ischaemia, but those to pattern reversal are generally inappropriate in sedated or anaesthetized subjects. For warning of ischaemia during surgery or intensive care, recording of peripheral potential to confirm entry of the

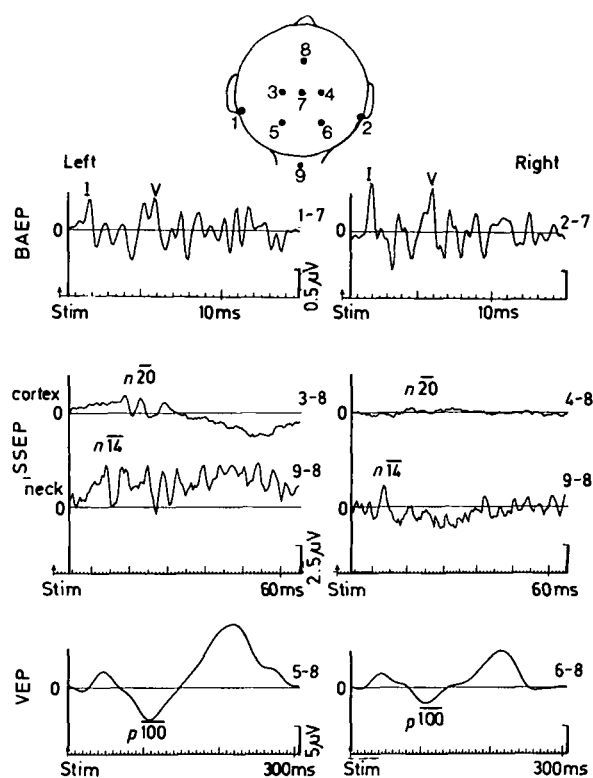


FIG. 4. Averaged sensory evoked potentials in traumatic coma: in a 24-year-old man 4 days after head injury with extensive cranial fracture on the right and underlying contusion. Fixed dilated pupils and no response to pain on admission; flexion of right limbs to pain after surgical debridement of the wound. Auditory brainstem potentials (BAEP), somatosensory potentials over 2nd cervical vertebra and contralateral somatosensory cortex following median nerve stimulation at the wrist (SSEP) and visual evoked potentials to binocular flash stimulation (VEP). Note slight delay of BAEP wave I on the right, but otherwise normal brainstem auditory potentials, depressed cortical SSEP and reduced amplitude VEP over the right hemisphere. Six weeks later, the patient was conscious and active with a left hemiparesis but no overt visual field defect; he was being transferred to a rehabilitation unit.

stimulus is an essential prerequisite to interpretation of abnormal cortical potentials.

Display and analysis of evoked potentials for ischaemia detection or serial assessment must permit simple quantification. Ischaemia affects amplitude more than latency with abolition of potentials when CBF is less than approximately  $15 \text{ ml min}^{-1}/100 \text{ g}$ . Focal ischaemia may produce significant amplitude asymmetry, but an amplitude ratio of 2 : 3 can be normal in cortical potentials in unanaesthetized subjects (Halliday, 1983). Greenberg, Mayer and others (1977), Lindsay and others (1981), Rappaport, Hall and others (1981) and Rappaport, Hopkins and others (1981) have used measures such as presence, number, complexity and symmetry of waves in the evoked potential as an index of preservation of function. This is useful for cortical potentials but unfortunately sedation, anaesthesia and hypothermia readily depress all but their primary components. In contrast, the more robust BAEP and CCT latencies are unaffected; they reflect subcortical functions and are more amenable to simple measurement.

#### THRESHOLDS FOR ISCHAEMIA AND BRAIN DAMAGE IN MAN

Although experimental observations have provided

valuable fundamental understanding of ischaemic brain damage, it is oversimplistic to extrapolate from them to clinical practice. In man, arterial hypertension and occlusive vascular disease in extracranial portions of the cerebral arteries are common compared with experimental animals. Many accidental insults are complex, with, for example, mixed hypoxia and ischaemia or combinations of local brain injuries, impairment of autoregulation and adverse systemic factors. Average "safe" values for cerebral perfusion may not necessarily apply to any one individual. The variations in CPP thresholds for electrical abnormality and extinction in different clinical circumstances are wide (table I) and are now illustrated by clinical examples.

#### Controlled hypotension

Since the introduction of this technique to produce a bloodless field during surgical anaesthesia, there have been anxieties regarding the effects on perfusion of brain and other organs (Review, 1975; Heuser, McDowall and Hempel, 1984). Although there are many experimental data, only a few investigators have mentioned thresholds, usually MAP of 20–40 mm Hg, for EEG deterioration or failure in man. This is probably partly because of inherent dif-

TABLE I. Mean thresholds for ischaemia-induced EEG or sensory evoked potential abnormality for various species and types of stress.  
† Not stated

Model	Cerebral perfusion pressure or mean arterial pressure* (mm Hg)		
	Control	Onset EEG or SEP abnormality	EEG or SEP silence
Profound hypotension (TMP) <i>M. mulatta</i> Brierley and others (1969)	†	30	25
Hypoxic hypoxia ( $P_{aO_2} < 20 \text{ mm Hg}$ ) <i>P. anubis</i> <i>M. mulatta</i> Brierley and others (1980)	$118 \pm 19$ $101 \pm 15$	$106 \pm 27$ $81 \pm 24$	$96 \pm 27$ $55 \pm 34$
Cardiac surgery* Onset bypass Later decreases Prior and others (in preparation)	$79 \pm 13$ $81 \pm 15$	$44 \pm 12$ $24 \pm 10$	15 $21 \pm 4$
Controlled hypotension* SNP TMP Thomas and others (1985)	$69 \pm 16$ $69 \pm 12$	$61 \pm 10$ $54 \pm 8$	— —
Traumatic coma Prior and others (1982)	54–60	$31 \pm 13$	$24 \pm 12$



difficulties in EEG quantification. Patel (1981) used the CFM, a monitor that had provided simple quantification in other circumstances. He was able to show in 45 healthy patients that the degree of depression of the monitored EEG was related to the rate of decrease of arterial pressure induced by a combination of ganglion and beta blockade with head-up tilt. EEG changes were minor unless pressure was reduced rapidly and was less than a systolic value of 60 mm Hg. Thomas and colleagues (1985) demonstrated that every patient in a group of 20 studied during routine surgical procedures, showed a decrease in EEG amplitude (measured by the CFM and by Fourier analysis) as MAP was reduced electively by sodium nitroprusside (SNP) or trimetaphan (TMP). The amplitude decline began once MAP decreased below a mean threshold of  $57 \pm 9$  mm Hg (table I). In almost half the patients there was a highly significant correlation between simultaneous 10-s measurements of MAP and average CFM voltage whilst MAP was decreasing. In no instance was there any suggestion of neurological sequelae. The degree of EEG depression was significantly greater below MAP 50 mm Hg with TMP than SNP (fig. 5), confirming the experimental find-

ings of Ishikawa and McDowall (1981), whose study is particularly important. A clear relationship was demonstrated between CBF and EEG "power" measured by the average voltage of the CFM trace during hypotension and both were significantly better sustained by SNP than TMP at equivalent low values of arterial pressure.

Experimental and clinical observations in controlled hypotension reveal wide inter-individual differences in cerebral effects of ischaemia such as the thresholds for alterations in CBF, EEG and evoked potentials. They are not entirely predictable on the basis of age, previous MAP or method and rate of pressure reduction. Nonetheless, there appears little evidence that major depression of CBF or electrical activity occurs at MAP greater than 60 mm Hg in normotensive patients who are presumed capable of autoregulation. Furthermore, there may be little benefit, in terms of reducing blood loss, in decreasing pressure to less than this value (Donald, 1982). If greater hypotension is necessary, for example in neurosurgery, presently available evidence suggests slow induction by SNP rather than TMP, under EEG or evoked potential control, to minimize the risks of ischaemic brain damage (McDowall, 1985).

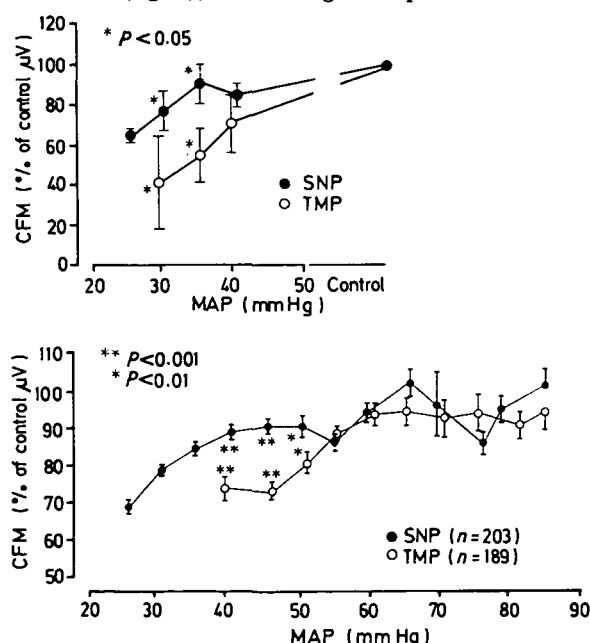


FIG. 5. Controlled hypotension, comparison of sodium nitroprusside (SNP) and trimetaphan (TMP) in cat (Ishikawa and McDowall, 1981) and man (Thomas et al., 1985). Mean CFM voltages as percentage of control for grouped data from 10 animals and 20 patients. (Redrawn from above with permission of authors and publisher.)

#### Cardiac surgery with cardiopulmonary bypass

Reduction in arterial pressure is one of many factors that may disturb the brain at the onset of cardiopulmonary bypass and subsequently during cardiac surgery (Branthwaite, 1975). Gaseous or particulate emboli, haemodilution and non-pulsatile flow may also contribute to brain damage, despite careful precautions. In spite of many factors involved, data from intraoperative polygraphic recordings in man provide useful evidence concerning thresholds for brain ischaemia.

EEG alterations are common at the onset of bypass with clear deterioration in approximately 63% of patients (Branthwaite, 1973a). Abnormalities appear when MAP decreases to less than a critical value in the region of 50 mm Hg (Junega, Flynn and Berger, 1972; Branthwaite, 1973b) or when the arterio-venous difference is less than 45 mm Hg in children (Harden, 1965). Most resolve in 5 min (Wright et al., 1972). Even with high flow rates, it is suggested that CBF decreases by approximately 50% at the onset of bypass (Branthwaite, 1974). The severity of the EEG abnormality is related consistently to the degree of hypotension (Branthwaite, 1973b; Pronk, 1982) with minor and major abnormalities at MAP of 46 and 37 mm Hg,

respectively.

Kriticou and Branthwaite (1977) compared groups of patients before and after the introduction of measures designed to maintain adequate cerebral blood flow (by vasopressors) and prevent microemboli. Although EEG alterations remained frequent, they were usually trivial and neurological deficits decreased from 19.2% to 7.4% or less. Low arterial pressures ( $33 \pm 10$  mm Hg at onset of bypass and  $24 \pm 10$  mm Hg in other hypotensive episodes) correlated significantly with EEG abnormality (Prior, Dimitri, Ellis, Etherington, Hinds and Rees, in preparation). When associated relative hypocapnia was avoided, the incidence of EEG abnormalities at onset of bypass was halved. Presumably the hypocapnia had already reduced CBF before arterial pressure decreased with onset of bypass and this increased the risk of cerebral ischaemia. There was some presumptive evidence of autoregulation of CBF, EEG abnormality often being briefer than hypotension. The relative timings were comparable to those obtained by Ekström-Jodal (1970) for acute decreases in arterial pressure and suggest that the early EEG recovery may result from cerebral autoregulatory mechanisms. This suggestion was supported by a higher MAP threshold ( $36 \pm 9$  mm Hg) for EEG abnormality in older and hypertensive patients than in the remainder ( $27 \pm 10$  mm Hg) ( $P < 0.05$ ). The negligible effect of hypothermia ( $20^\circ\text{C}$ ) on autoregulation of CBF suggested by Fox and others (1982) does not suggest lack of risk of cerebral ischaemia. Their MAP are low, but there is insufficient evidence in man to define critical limits for hypothermic subjects. An added difficulty is the similar effect of ischaemia and profound hypothermia on the EEG.

Ischaemic brain damage assessed clinically and neuropathologically is related clearly to low MAP values during operation, prolonged bypass and age. Javid and others (1969) showed that arterial pressures less than 60 mm Hg for 5–132 min (temperature not stated) were followed by neurological deficit, behavioural disturbance and intellectual impairment. These deficits tended to resolve or improve with time in most survivors but, in those who died, histological evidence of cortical infarction and lesser ischaemic alterations were found. Branthwaite (1972) reported episodes of circulatory embarrassment in 24 of 32 patients with neurological deficit after operation. Unfortunately, in the absence of circumstantial evidence from polygraphic recording, it may not be possible to incrimi-

nate ischaemia, since gas embolism produces similarly distributed EEG neuropathological changes (Arfel and Naquet, 1974).

Schwartz and colleagues (1973) used intra-operative EEG (recorded by a CFM) to predict either uncomplicated recovery or graded neurological deficit in 100 patients. The predictions were accurate in 83%. Malone, Prior and Scholtz (1981) surveyed all 20 patients, in an 8-year period from the same unit, who had died at any stage after bypass operations and had been examined neuropathologically. CFM abnormalities during operation correlated with the incidence and extent of ischaemic damage which was always of arterial boundary zone distribution. However, a critical degree and duration of CFM depression (at least 7 min major depression) during hypotension was evidently necessary before clinical or histological ischaemic brain damage was found.

Thus, during cardiac surgery, EEG abnormality appears when arterial pressures are too low for the individual; sustained abnormality predicts the occurrence and severity of neurological deficit and ischaemic brain damage.

#### *Carotid artery surgery*

Focal cerebral ischaemic damage is a significant risk during the period of carotid clamping necessary for disobliteration or grafting, or both. Ischaemia is not the only cause of brain damage: embolism and hypotension also endanger the patient. Hypotension triggers infarction in many previously well compensated patients with extracranial obstruction of cerebral arteries (Yates and Hutchinson, 1961). Causation of neurological deficit following surgery can often be identified in anaesthetized patients by the timing of EEG abnormalities during or after operation.

The consensus of clinical reports is that when regional CBF after carotid clamping decreases to less than  $24\text{--}18\text{ ml min}^{-1}/100\text{ g}$ , EEG abnormalities (slowing and flattening) occur (Trojaborg and Boysen, 1973; Sharbrough, Messick and Sundt, 1973). These are usually reversed immediately by shunting (Sundt et al., 1981), otherwise there is danger of infarction.

Internal carotid artery stump pressures have been considered unreliable indicators for shunting because of the influence of anaesthesia and poor correlation with CBF (McKay et al., 1976). When CBF decreases to less than  $18\text{ ml min}^{-1}/100\text{ g}$ , reversible "physiological paralysis" attributed to local cerebral metabolic changes is observed in patients operated

on under regional anaesthesia (Sundt et al., 1977). Experimental evidence suggests that such flows may be tolerated for up to 2 h (in healthy non-arteriopathic subjects) before infarction (Sundt and Michenfelder, 1972; Jones et al., 1981). However, if CBF of  $10 \text{ ml min}^{-1}/100 \text{ g}$ , or less, occurs, there is immediate risk of infarction. Obviously, if patients are operated upon under general anaesthesia, the early warning of clinical deficit is not available and the use of EEG as a non-invasive functional monitor becomes necessary.

Conventional multichannel EEG monitoring is limited to a few devoted practitioners because of its complexity; most turn to computer-aided processing (Myers, Stockard and Saidman, 1977; Chiappa, Burke and Young, 1979). The utility of a large amount of intra-operative EEG frequency information is open to dispute. The only EEG sign predicting a poor outcome in one series was voltage attenuation (Chiappa, Burke and Young, 1979). This probably accounts for the success of simpler EEG monitors such as the CFM, provided electrode placement is appropriate. When a pair of ipsilateral centro-parietal CFM leads was used during carotid endarterectomy, changes seen on the 16 channel EEG were identified in nine of 11 patients with regional CBF less than  $18 \text{ ml min}^{-1}/100 \text{ g}$ . In the remaining two, the CFM trace was unaltered despite flows of 7 and  $15 \text{ ml min}^{-1}/100 \text{ g}$ , and the simultaneous conventional EEG showed only very minor alterations (Cucchiara et al., 1979). About 25% of patients may require shunting during carotid clamping because low flows lead to EEG abnormality. Patients with flows in the range  $20\text{--}30 \text{ ml min}^{-1}/100 \text{ g}$  may also benefit from shunting to avoid internal capsule ischaemia which may not be revealed by CBF or EEG, both of which essentially reflect cortical function (Sundt et al., 1977). This problem could be addressed by combining EEG monitoring with the use of somato-sensory evoked potentials (Markand et al., 1984) which traverse the internal capsule.

#### *Subarachnoid haemorrhage and intracranial aneurysm surgery*

Evoked potentials have been used as measures of ischaemia in patients with subarachnoid haemorrhage. They may be more relevant than EEG because lesions produced by arterial spasm may not extend to the convexity of the brain to become accessible for EEG monitoring. The central somatosensory conduction time (CCT, see above) may be

assessed with external electrodes and a small portable averaging computer. Correlations with ischaemia have been demonstrated clinically (Symon et al., 1979).

An alternative technique has been the use of the rather unphysiological "direct cortical response" (Eisenberg et al., 1979). This is a potential elicited by direct electrical stimulation of the cerebral cortex at craniotomy with recording from closely adjacent electrodes. The potential reflects the local CBF and was reduced when MAP was less than 60–70 mm Hg, but still detectable at 37 mm Hg when the underlying electrocorticogram had become isoelectric. The potential faded at pressures below 25 mm Hg, but recovered when MAP was restored. It was proposed as a test of the patient's ability to tolerate controlled hypotension or local ischaemia during intracranial aneurysm surgery.

#### *Head injuries*

Two periods of potentially avoidable risk for ischaemic brain damage occur in comatose patients with severe head injuries. Soon after trauma, especially in those with multiple injuries, there is risk of hypoxia and hypotension (Miller et al., 1978). Later, increasing brain swelling, inadequately controlled seizures or perhaps inadequate sedation, may render a poor oxygen delivery insufficient for the metabolic needs of the brain. Neuropathologists have demonstrated over 90% incidence of ischaemic brain damage along arterial boundary zones in patients dying from non-missile head injuries (Graham, Adams and Doyle, 1978). The damage was attributed to reduced perfusion pressure and considered an important cause of mortality and morbidity. This is supported by evidence of increased morbidity and mortality from early hypoxia and hypotension and poorly controlled epilepsy (Price and Murray, 1972; Rose, Valtonen and Jennett, 1977; Miller et al., 1978). Studies of CBF in traumatic coma have shown that ischaemic values (less than  $17\text{--}20 \text{ ml min}^{-1}/100 \text{ g}$ ) occur early after injury, have a fronto-parietal artery boundary zone distribution and are associated significantly with a poor outcome (Overgaard, Mosdal and Tweed, 1981; Overgaard and Tweed, 1976, 1983).

EEG correlates of cerebral ischaemia can be demonstrated by continuous polygraphic recording (fig. 6, table I). When increased intracranial or decreased arterial pressure, or both, critically reduce cerebral perfusion, EEG and cortical evoked potentials decline in amplitude and then become

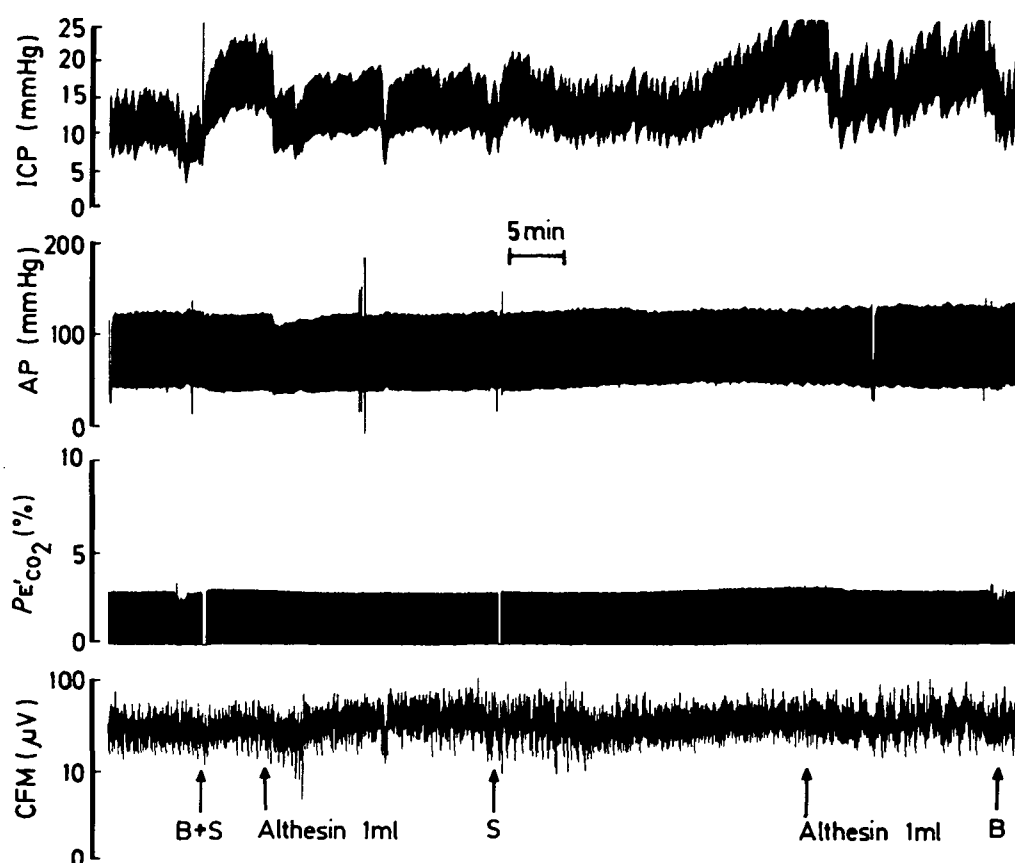


FIG. 6. Head injury: polygraphic recording of intracranial and arterial pressures, end-tidal carbon dioxide and CFM in a 7-year-old girl, 3 days after head injury. On admission, extensor responses of right and flexor responses of left limbs. Infusion of Althesin at  $6 \text{ ml h}^{-1}$  and fentanyl  $1 \text{ ml h}^{-1}$ ; controlled ventilation. Note effects of Althesin boluses (1 ml) and also short term fluctuations in ICP reflected by CFM trace. Subsequent full recovery, returning to school 10 weeks after injury. B=bagging; S=suction.

silent. The mean threshold for EEG depression in eight patients was a CPP of  $31 \pm 13 \text{ mm Hg}$  and that for electrical silence at  $24 \pm 12 \text{ mm Hg}$  (Prior et al., 1982; Prior and Hinds, in preparation). Perfusion pressures of this order leading to electrical silence may be tolerated for several minutes without damage, providing corrective action is taken speedily to restore CBF. Potentials evoked by various modalities of sensory stimulation have an important role in mapping the integrity of specific functional pathways (fig. 4) and are of considerable prognostic value (Greenberg, Becker et al., 1977; Greenberg, Mayer et al., 1977; Hume and Cant, 1981; Lindsay et al., 1981; Narayan et al., 1981; Rappaport, Hall et al., 1981; Rappaport, Hopkins et al., 1981). Evoked potentials are most valuable when prevention or treatment of brain ischaemia involves use of muscle

relaxant drugs with controlled ventilation and when major sedatives are used. Unlike clinical neurological testing, none of the evoked potentials depends on a motor response and the short latency components are unique in being virtually unaffected by sedation or anaesthesia sufficient to render the EEG silent (Stockard and Sharborough, 1979; Ganes and Lundar, 1983). The ischaemic thresholds for extinction of evoked potentials in patients with head injury are not yet fully defined.

Correlations between EEG, CBF and oxygen metabolism in the injured brain are difficult because of the direct effects of trauma. EEG signs of local injury, seizure discharges and projected slow-wave abnormalities from brainstem injury (Evans, 1976; Schwartz and Scott, 1978) impinge upon what may be relatively normal background rhythms. The pro-

jected slow waves are accompanied by increased brain metabolism and are paradoxical both in terms of arousal mechanisms and EEG/metabolic correlates. Because of such phenomena, EEG must be classified by significant clusters of patterns rather than by single frequency or amplitude measurements. Thus Bricolo and others (1978) and Bricolo, Faccioli and Turazzi (1979) (from a prodigious monitoring study of 1600 comatose patients) grouped EEG according to the presence or absence of "changeability". They have shown variations in associated mortality rates from 8% for a changeable sleep-like, 41% for an alternating to 86% for an unchanging slow pattern and 100% for a silent EEG. Modification of their classification to include EEG responses to painful stimuli has been used for studies correlating EEG with cerebral metabolic rate for oxygen (CMRO<sub>2</sub>) and regional CBF (Prior et al., 1982; Overgaard, Prior and Rosendal, in preparation). This has revealed a general trend to increasingly impoverished CBF and CMRO<sub>2</sub> as the severity of EEG abnormality increases. Most significant was that one-third of regional CBF values were less than 20 ml min<sup>-1</sup>/100 g and predominantly of arterial

boundary zone distribution in the patients with non-reactive unchanging EEG; they all were followed by death or severe disability. Correlative studies between neurophysiological measures and ultimate neuropathology will be of considerable interest.

#### *Seizures and status epilepticus*

The increased cerebral metabolism occurring with major seizures leads to ischaemic brain damage if oxygen delivery is insufficient. Intracranial pressure may increase with each seizure discharge (Gabor et al., 1984). Burst firing of neurones produces paroxysmal depolarization with Ca<sup>2+</sup> entry to neurones reaching toxic concentrations. Increased ATP turnover and mitochondrial metabolism can produce mitochondrial failure with microvacuolation and release of Ca<sup>2+</sup>. This activates protease and phospholipids and results in ischaemic cell change selectively affecting those neurones most actively discharging (Meldrum et al., 1984; Simon et al., 1984). Prevention of ischaemic damage rests in part on establishing, by EEG monitoring, that all discharges have been abolished by appropriate anti-epileptic therapy.

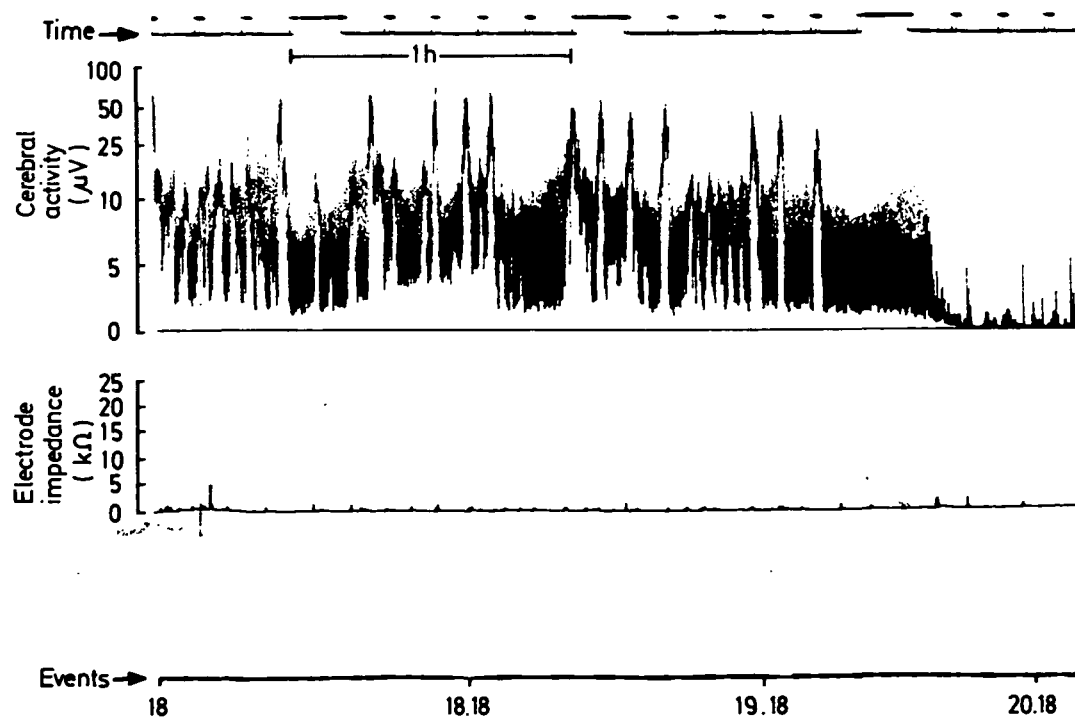


FIG. 7. Status epilepticus: CFM recording in a 52-year-old man comatose after severe head and multiple injuries with possible fat embolism. Each peak corresponds to a seizure discharge with minor clinical accompaniments. Terminal bradycardia is associated with failure of cerebral perfusion and EEG activity declines towards zero.

Status epilepticus has systemic complications including hyperthermia, hypoxia, hypotension, hypoglycaemia and motor exhaustion that can be avoided by intensive care which includes controlled ventilation and muscle paralysis. This obviates ischaemic damage in the cerebellum. However, unless all seizure discharges are controlled (even though they are not expressed clinically because of muscle paralysis) ischaemic damage still occurs, especially in the hippocampus and cerebral cortex (Blennow et al., 1978). The role of EEG monitoring is thus to determine if paroxysmal electrical discharges have been abolished or to quantify the efficiency of various anti-epileptic drugs (Pampiglione and da Costa, 1975; Eyre, Oozeer and Wilkinson, 1983). Seizure discharges (fig. 7) may be quantified in terms of duration and repetition rate. The longer clinical convulsions or electrical discharges last, the greater is the likelihood of brain damage (Rowan and Scott, 1970; Oxbury and Whitty, 1971; Aminoff and Simon, 1980).

#### Cardiac arrest

The occasions when EEG monitoring is in progress at the time of cardiac arrest and resuscitation must be relatively few. However, there is evidence that the duration of the electrical silence that follows total cerebral circulatory arrest is related inversely to the quality of outcome. In a personal series of 371 patients (916 EEG), studied soon after resuscitation, 149 had isoelectric EEG. Of these, only two (with drug overdose) recovered fully; two survived in vegetative states and the remainder died. Clinical and neuropathological examination in 24 gave evidence

of a typical distribution of damage affecting the neocortex but not the brainstem. EEG and evoked potential abnormalities are consistent with the severity and distribution of ischaemic damage (Lindgren, Petersen and Zwetnow, 1968; Brierley et al., 1971; Prior, 1973; Trojaborg and Jørgensen, 1973; Starr, 1975; Uziel and Benezech, 1978).

In an important study of all episodes with circulatory arrest over an 8-year period in two Copenhagen hospitals, Jørgensen and Malchow-Møller (1981) examined 613 patients. The circulation was successfully restarted in 329; after exclusion of patients with overdose or with pre-existing cerebral abnormalities, there remained 125 who had no detectable EEG immediately after resuscitation. These latter patients were followed with EEG monitoring and serial neurological assessment. An orderly sequence of recovery of EEG features and related neurological signs was observed in patients recovering (table II). Whilst the EEG remained isoelectric, first the pupils became smaller, then all cranial nerve reflexes except the caloric-vestibular returned. Next, motor responses appeared, predominantly decerebrate (extension of all limbs and neck) posturing. At this stage intermittent EEG activity appeared, followed by medium sized pupils, decorticate (flexion of the upper and extension of the lower limbs) posturing and stereotyped reactivity to stimuli (repetitive grimacing, eye movements, swallowing, yawning, chewing, respiratory alterations, or other movements without defence or escape characteristics). Next the EEG became continuous whilst stereotyped responses persisted; consciousness was then regained and basic motor, sensory and mental

TABLE II. Cardiac arrest: data based on Jørgensen and Malchow-Møller (1978, 1981) with permission, to indicate longest interval after resuscitation for various clinical and EEG signs to appear if the patient is going to recover (a) any function, (b) consciousness or (c) full restoration of all their faculties within 1 year. (Descriptions of terms are given in the text)

Clinical and EEG features	Longest delays (from time of resuscitation) for appearance of clinical or EEG features compatible with:		
	(a) any functional recovery	(b) recovery of consciousness	(c) full recovery by 1 year
Respiratory movements	15 min	7 min	
Pupillary light reflex	28 min	12 min	
Coughing/swallowing reflex	58 min	23 min	
Caloric vestibular reflex	15 h	2.75 h	
Decorticate posturing	9 h	3 h	
Stereotyped reactivity	7.5 h	3 h	
EEG - intermittent	7.5 h	3.3 h	3 h
EEG - continuous	17 h	10.5 h	
Consciousness			2 days
Speech			6.5 days
Coping with personal needs			2 weeks

faculties returned gradually. In contrast, brain death could be predicted by cranial nerve areflexia with loss of spontaneous respiratory movements, often accompanied by dilated pupils, spinal reflexes, poikilothermia and diabetes insipidus (see also Jennett, 1981; Pallis, 1983). Intermittent or continuous EEG activity containing sharp waves or spikes and extension or flexion reflexes predicted an unfavourable outcome. In such patients, some cranial nerve reflexes usually recovered with the abnormal EEG activity; both might disappear abruptly or regress in a pattern reversing the order of their earlier recovery. Such deterioration was always secondary to cardiovascular or pulmonary complications. The neuropathological examinations in this large series showed extensive neuronal loss when adverse EEG and clinical signs had persisted for more than 72 h.

#### EEG AND EVOKED POTENTIAL MONITORING DURING TREATMENT OF BRAIN ISCHAEMIA

The treatment of brain ischaemia is primarily preventative: prevention of the original insult and prevention of its consequences which may lead to a chain of events that worsen brain damage. Neurophysiological monitoring has a role in both. The brain may be "protected" by reducing the metabolic needs to the levels available (by hypothermia, anaesthesia or sedation), preventing high demands (control of seizures, avoidance or blocking of painful and other stimuli), and ensuring optimal oxygenation and perfusion (controlled ventilation, maintenance of fluid volume, arterial pressure and reduction of increased intracranial pressure).

EEG monitoring ascertains the level of sedation achieved and identifies when stimulus-induced arousal responses increase metabolic demands. It permits recognition of seizure discharges even when clinical accompaniments are masked by drugs and indicates when reduction of cerebral perfusion has become critical. It helps to guide the administration of boluses of sedatives before painful procedures in intensive care (Kassell et al., 1980; Prior et al., 1983). Experimental observations (Michenfelder, 1974) suggest that such boluses have no effect on intracranial pressure if a silent EEG is present (indicating that maximal metabolic depression already exists). Studies in man with etomidate boluses (Bingham, Procaccio, Hinds and Prior, in preparation) and Althesin (Procaccio, Bingham, Hinds and Prior, in preparation) lend support to this view.

Evoked potentials are useful as an adjunct to EEG monitoring when treatment involves massive sedation. This abolishes motor function and EEG, but

does not affect the short latency auditory brainstem and somatosensory evoked potentials (Stockard and Sharbrough, 1979; Sutton et al., 1982; Ganes and Lunder, 1983).

Hypothermia affects the BAEP with increase in wave V-I latency of the order of 4–6% per °C cooling (Marsh, Yamane, and Potsic, 1984); these authors comment that such prolongation "does not inevitably reflect a pathological state. Rather it is an expression of a lawful relationship between temperature and the rate of electrochemical processes underlying nerve conduction and synaptic process". In contrast, with the SSEP, whilst peripheral nerve sensory conduction velocity decreases during cooling by  $2 \text{ m s}^{-1} \text{ }^{\circ}\text{C}^{-1}$ , CCT is reported to be unaffected (Gilmore and Lastimosa, 1984).

During intensive treatment of a patient whose brain has been ischaemic it is important to differentiate between those electrical abnormalities produced by damage already inflicted, those from depression by therapeutic agents or hypothermia and those induced by continuing low perfusion states. It is here that a combination of neurophysiological techniques aids management and prognostication.

#### CONCLUSIONS

Monitoring of EEG and evoked potentials is indicated when there is risk of cerebral ischaemia during elective procedures and to provide information on the functional state of the central nervous system during treatment of comatose patients.

When EEG power or amplitude begins to decrease or evoked potential latencies increase, it does not follow that brain damage has occurred. It is a warning that cerebral blood flow or oxygen delivery is impaired and that the patient is at risk of ischaemia and time is limited. Damage occurs after several minutes of electrical silence.

The most effective monitors display continuous amplitude of EEG, filtered to exclude potentially artefactual slow waves. They also indicate frequency content, for example in a combined power-amplitude display.

During surgical procedures such as cardiopulmonary bypass or induced hypotension when global cerebral ischaemia is a risk, bilateral EEG monitoring is appropriate. For warning of focal ischaemia (for example during carotid artery surgery), appropriately lateralized recording should be compared with control data from the contralateral hemisphere. If risk of ischaemia is mainly to subcortical structures (e.g. after subarachnoid haemorrhage),

somatosensory evoked potential are more helpful than EEG.

In comatose patients, EEG monitoring warns of impending ischaemia when a critical reduction of cerebral perfusion occurs and also allows recognition of increased metabolic demands, for example with seizure discharges or marked reactivity to pain.

Evoked potentials are indicated for mapping the integrity of various sensory pathways after trauma and as a means of assessing central nervous function when clinical and EEG signs are depressed by major sedatives.

#### ACKNOWLEDGEMENTS

Many colleagues in departments of anaesthesia, intensive care, cardiothoracic and neurological surgery, medical electronics and neuropathology have given much help and advice. I am especially grateful to Dr J. B. Brierley, Mr N. J. Etherington, Mr D. S. L. Lloyd, Dr M. Matoušek, Dr D. E. Maynard, Miss Valerie Sharpe and the late Professor J. Overgaard. The Joint Research Board of St Bartholomew's Hospital and Medical College and The British Council have given financial help for some of our collaborative studies.

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