

## ***Electroencephalogram (EEG)***

The EEG is a recording of the brain's electrical activity, in most cases made from electrodes over the surface of the scalp. It may also be made from electrodes placed directly over the surface of the brain or from needle electrodes inserted into the brain. The recordings are the summation of volume conductor fields produced by millions of interconnecting neurones. The neurone components producing the currents are the dendrites, axons and cell bodies. The architecture of the brain is not uniform but varies with different locations. Thus the EEG can vary depending on the location of the recording electrodes.

Sensory information is transmitted to the brain by frequency modulated trains of action potentials which cause neurone activity in particular regions of the brain depending on the type of sensory information and the site of stimulus in the body. Similarly the decision to initiate a movement, in response to sensory information, arises in various parts of the brain, depending on the type of movement and its location in the body, and gives rise to electrical activity at the corresponding sites.

When analysing the EEG it is convenient to think of the brain as three sections: cerebrum, cerebellum and brain stem. The brain stem is the oldest part in evolutionary terms, and its structure, size and function have changed little in the evolution of the vertebrates. It is an extension of the spinal chord and has three main functions:

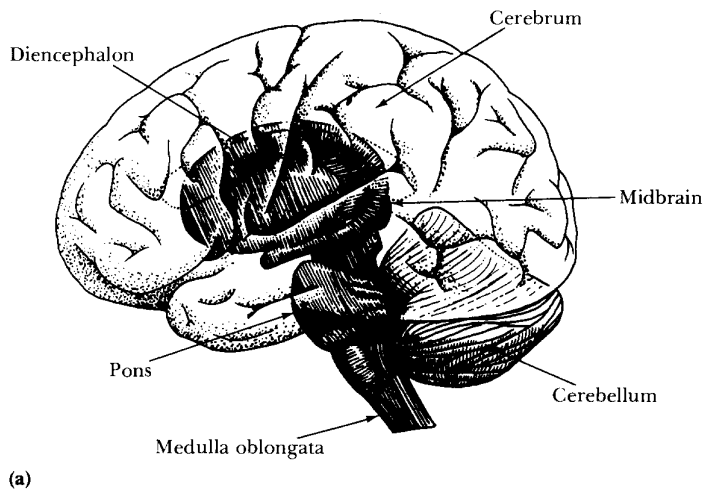
1. Connecting link between the cerebral cortex, cerebellum and spinal chord,
2. Control centre for basic body functions such as respiration, heart and blood flow regulation,
3. Integration centre for complex reflexes, such as maintenance of body position and posture.

The cerebellum coordinates voluntary muscle movements and maintains balance. The cerebrum is the dominant part of the central nervous system and has centres for conscious appreciation of sensation, initiation of movement, complex analysis and expressions of emotions and behaviour (Figure 94).

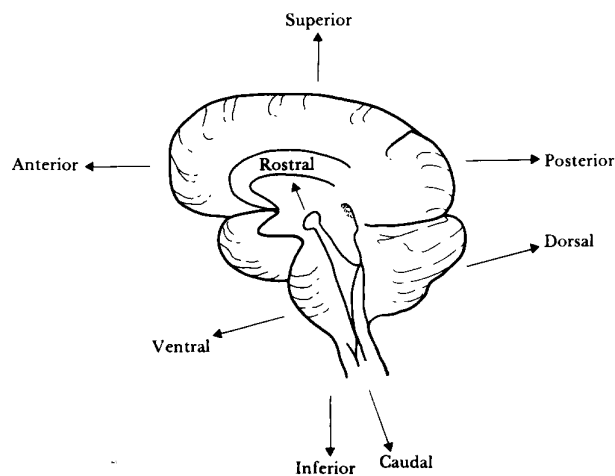
### *Cerebrum*

The cerebrum consists of two hemispheres. The right one senses information from the left side of the body and controls movement on the left side. Similarly the left hemisphere is connected to the right side of the body (Figure 95). The cerebrum consists of several layers. The outer layer, approximately one centimetre thick, consists mostly of neurone cell bodies, which give it a grey appearance. The surface is highly convoluted with ridges (gyri) and valleys (sulci). The main, deeper sulci are called fissures. Beneath the outer layer are axons, which have a white appearance. Embedded in the white matter are further collections of cell bodies called nuclei. Some of the functions of the cerebrum are localised within specific anatomical structures, some are more widely distributed.

The cerebral cortex contains six layers (Figure 96). There are two types of neurone cell bodies: pyramidal cells and stellate (granule) cells. The pyramidal cells are large



(a)



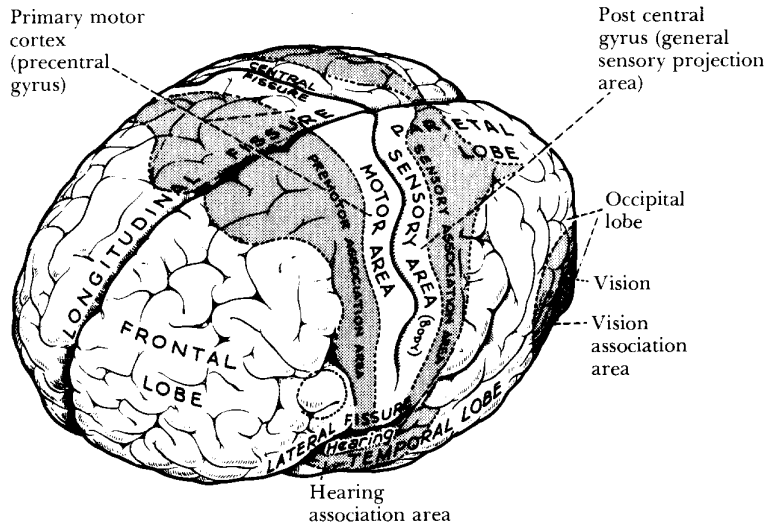
(b)

**Figure 94 Lateral view of brain showing brainstem structures (medulla, pons, midbrain and diencephalon) beneath lateral part of cerebral hemisphere, with cerebellum behind and below, (b) Orientation of brain to rest of body.**

and tend to connect to distant structures in other parts of the cerebrum, thalamus, cerebellum and spinal chord. There are many feedback connections. Granule cells are smaller and only connect with other cells in their immediate vicinity.

### *Brain Stem*

There are four regions: medulla oblongata, pons, midbrain and diencephalon. Each contains nuclei (groups of neurone cell bodies) and bundles of axons. The pons is a bulge at the upper end of the medulla (Figure 94). The medulla has motor and sensory areas for the mouth, neck and throat, and also controls the respiratory and cardiovascular systems.



**Figure 95 Cerebral hemispheres showing the motor areas (towards the front) and the sensory areas (towards the back).**

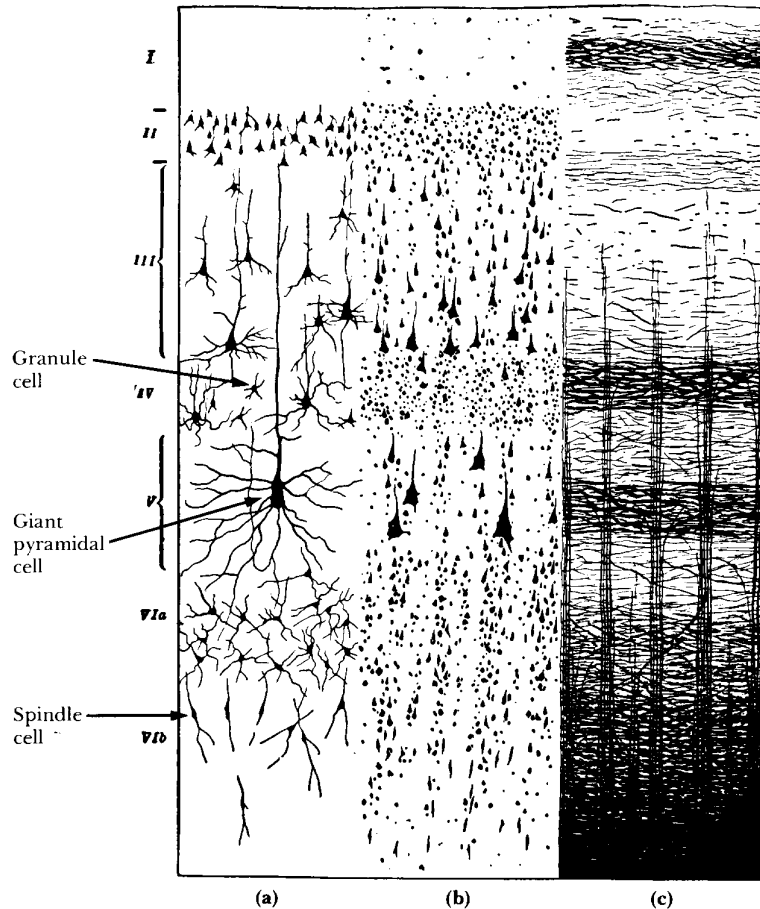
The pons contains cranial nerve nuclei associated with motor and sensory functions of the face. The midbrain contains the major nuclei that control eye movement, blinking and the pupillary light reflex. The diencephalon is at the upper end of the brain stem. It contains the thalamus that integrates sensation, before passing signals onto the cerebrum, and is the site where pain can be consciously appreciated.

### *Cerebellum*

The cerebellum integrates information from the cerebral cortex, the spinal chord and the vestibular system of the inner ears. The information from the cerebral cortex is motor information concerning where the brain is moving consciously the body and limbs. Information from the spinal chord originates in the position sensors in the joints, tendons and muscles of the body. Information from the vestibular system concerns the orientation of the head in three-dimensional space and its movement. The cerebellum thereby serves to coordinate movement and maintain posture.

### *Electrical Recordings from the Brain*

Recordings made from an electrode on the surface of the scalp, using a distance reference electrode, are the resultant field potential at the boundary of a large volume conductor containing many active neurones. Action potentials in axons contribute little to scalp surface records as they are asynchronous and the axons run in many different directions. Surface records are the net effect of local postsynaptic potentials of cortical cells. These may be both excitatory and inhibitory.

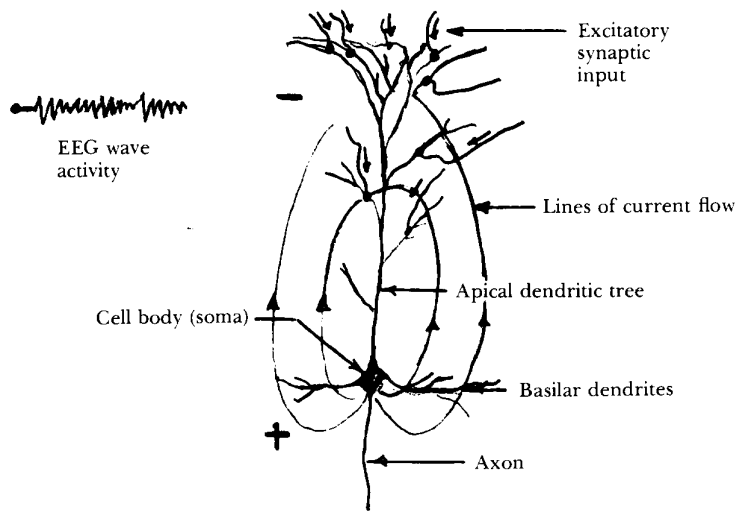


**Figure 96** Structure of the cerebral cortex, which consists of six layers, shown using three different stains under the microscope: (a) Golgi stain showing cell bodies and dendrites, (b) Nissl cellular stain, (c) myelin sheath showing axons. The six layers are: I molecular layer, II external granular layer, III external pyramidal layer, IV internal granular layer, V large or giant pyramidal layer (ganglionic layer), VI fusiform layer.

The current flow and contribution by a pyramidal cell to an overlying EEG electrode is shown in Figure 97. Each pyramidal cell acts as a radially orientated dipole. The total contribution at the surface depends on the staggered summation in space and the degree of activity at any given time. The orientation of the dipole reverses when most of the input at the dendrites is inhibitory.

### *Resting Rhythms of the Brain*

EEGs show continuous oscillating electric activity. The amplitude and the patterns are determined by the overall excitation of the brain which in turn depends on the activity of the reticular activating system in the brain stem. Amplitudes on the surface of the brain can be up to 10 mV, those on the surface of the scalp range up to 100  $\mu$ V. frequencies range from 0.5 to 100 Hz. The pattern changes markedly between states of sleep and



**Figure 97 A single pyramidal cell in the cerebral cortex showing the current flow generating contributions to the surface EEG during a net excitatory input. Polarity is reversed for a net inhibitory input.**

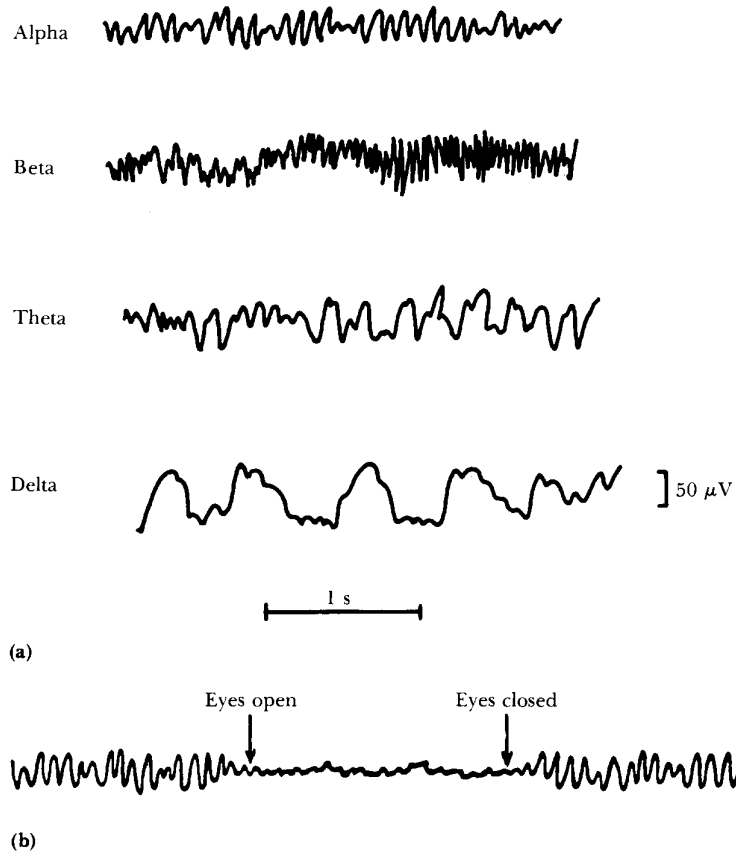
wakefulness. Distinct patterns are seen in epilepsy. Five classes of wave groups are described: alpha, beta, gamma, delta and theta (Figures 98, 99 and 100).

Alpha waves contain frequencies between 8 and 13 Hz with amplitude less than 10  $\mu\text{V}$ . They are found in normal people who are awake and resting quietly, not being engaged in intense mental activity. Their amplitude is highest in the occipital region. When the person is asleep, the alpha waves disappear. When the person is alert and their attention is directed to a specific activity, the alpha waves are replaced by asynchronous waves of higher frequency and lower amplitude.

Beta waves have a frequency range of 14 to 22 Hz, extending to 50 Hz under intense mental activity. They have their maximum amplitude (less than 20  $\mu\text{V}$ ) on the parietal and frontal regions of the scalp. There are two types: beta I waves, lower frequencies which disappear during mental activity, and beta II waves, higher frequencies which appear during tension and intense mental activity.

Gamma waves have frequencies between 22 and 30 Hz with an amplitude of less than 2  $\mu\text{V}$  peak-to-peak and are found when the subject is paying attention or is having some other sensory stimulation.

Theta waves have a frequency range between 4 to 7 Hz with an amplitude of less than 100  $\mu\text{V}$ . They occur mainly in the parietal and temporal regions in sleep and also in children when awake, and during emotional stress in some adults, particularly during disappointment and frustration. Sudden removal of something causing pleasure will cause about 20 s of theta waves.

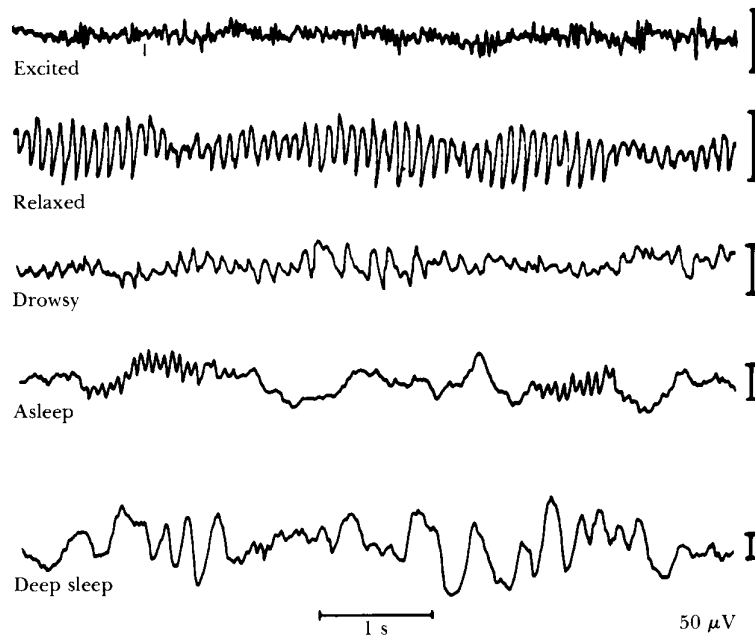


**Figure 98 (a) Normal EEG patterns, (b) change from alpha waves to asynchronous pattern when subject opens eyes.**



**Figure 99** Normal EEG patterns: (a) alert state, (b) drowsiness, (c) theta and beta waves, (d) moderately deep sleep (e) deep sleep.

Delta waves have a frequency content between 0.5 and 4 Hz with an amplitude less than 100  $\mu\text{V}$ . They occur during deep sleep, during infancy and in serious organic brain disease. They will occur after transections of the upper brain stem separating the reticular activating system from the cerebral cortex. They are found in the central cerebrum, mostly the parietal lobes.



**Figure 100 Normal EEG as subject goes to sleep. Calibration marks on right represent 50  $\mu$ V.** The production of any of these rhythmic waveforms requires that areas of cerebral cortex be connected to other areas and the reticular activating system in the brain stem.

### *Standard Electrode Placement*

The most commonly used placement standard is the International Federation 10-20 system (Figures 101 and 102). Three types of electrode connections are used (Figure 103):

1. Bipolar (between pairs of electrodes, usually adjacent)
2. Monopolar (between one electrode and a distant reference electrode usually attached to one or both earlobes)
3. Monopolar (between one electrode and a reference formed by averaging all the other electrodes by connecting them through resistors)

Electrodes are small, disposable, self-adhesive and contain their own electrode gel.

The EEG is usually recorded with the subject awake but resting on a bed with their eyes closed. Records may also be made with the subject asleep or when hyperventilating (over breathing). Both these conditions may give rise to abnormal patterns which may not be present in the resting state. During sleep the patterns are high amplitude, low frequency; except during REM (rapid eye movement) sleep when a low amplitude, high frequency component, similar to patterns when awake. During REM sleep the person is dreaming, the eyes are moving rapidly, as they might when awake and alert, and muscle tone is diminished through the body, except for the eye muscles.



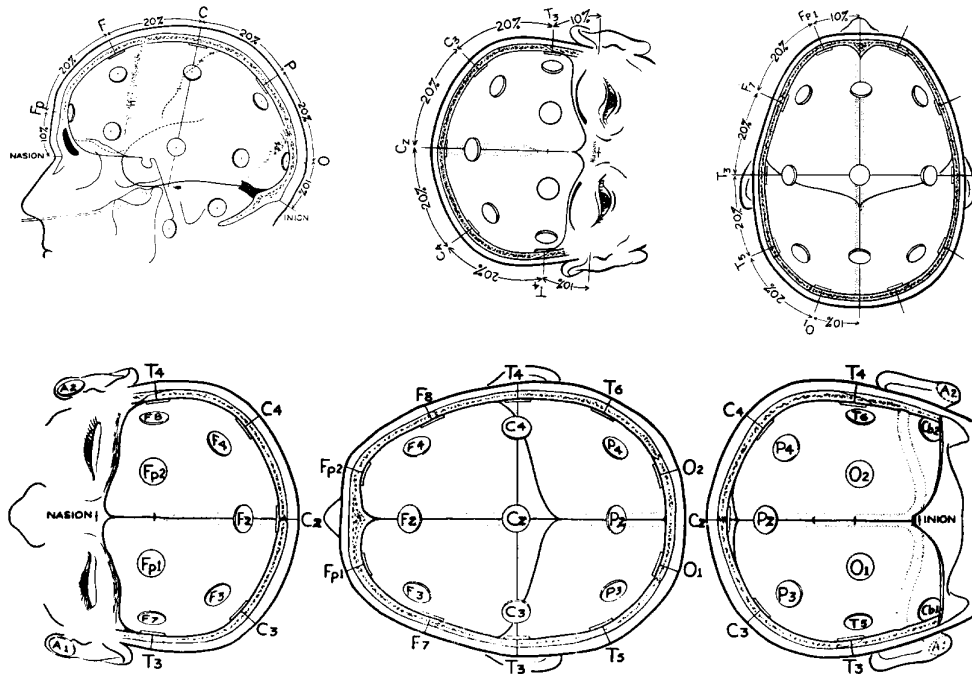


Figure 101 The 10-20 electrode system recommended by the International Federation of EEG Societies.

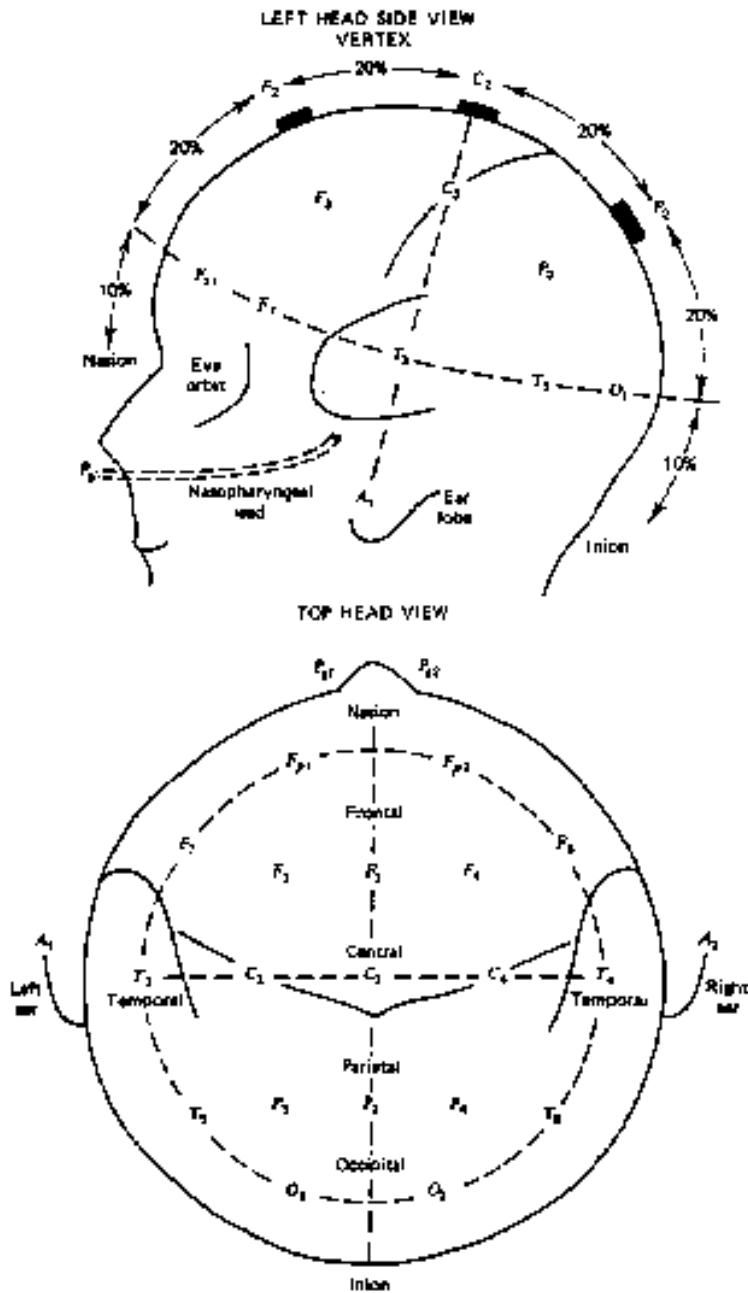


Figure 102 The 10-20 EEG electrode placement system.

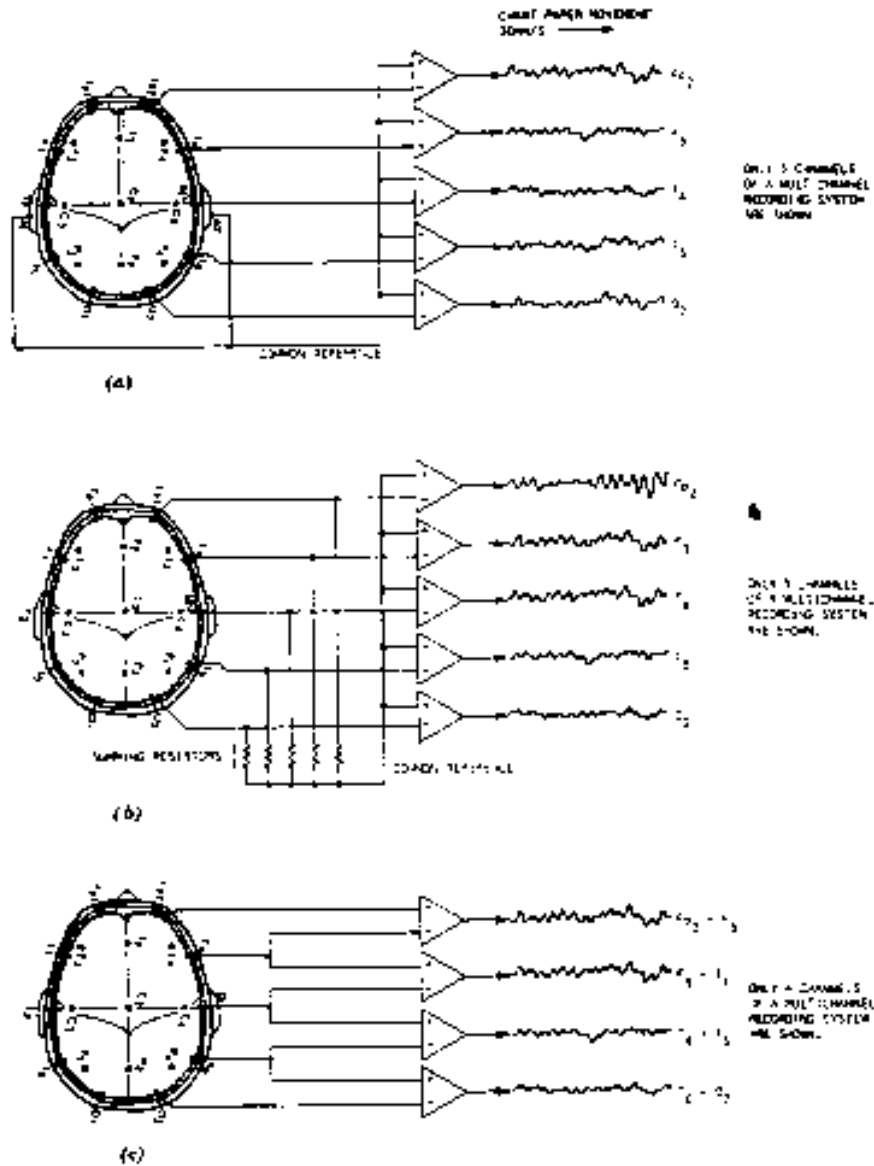
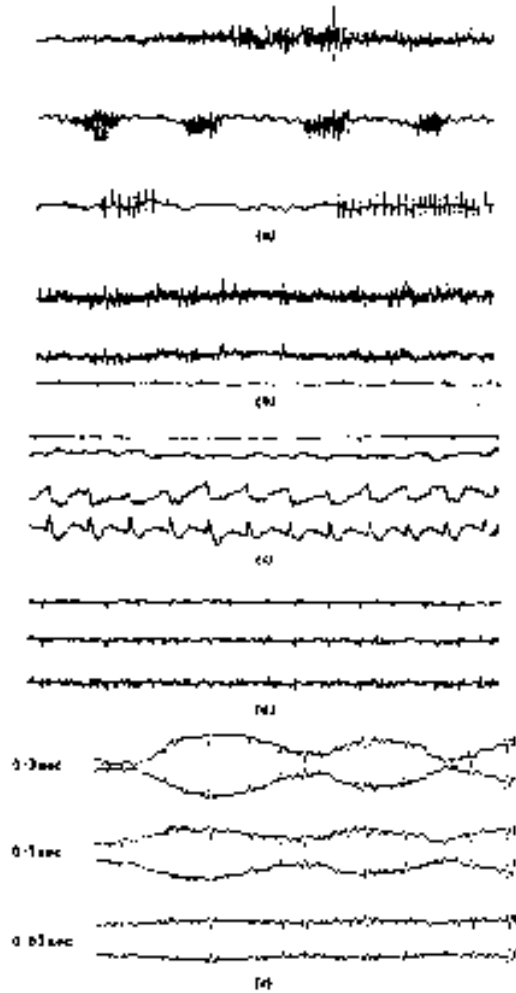


Figure 13 EEG recording modes: (a) unipolar, (b) average, (c) bipolar.

Artefacts may be produced by electrode variation and muscle activity in the face, scalp and eyes. The pulse may produce an artefact by altering the impedance between the brain and the electrodes at each heart beat. The ECG may be superimposed on the EEG. Sweating can produce a slow baseline drift. Incorrect gain, offset or filter settings will cause clipping, saturation and distortion of the signal (Figure 104).



**Figure 104 EEG artefacts: (a) scalp muscle activity, (b) muscle activity with low-pass filter with cut-off frequency of 25 Hz, (c) pulse artefact, (d) ECG artefact, (e) sweating with high-pass filters of progressively reducing time constants.**

### *Recording Systems*

Ten and twenty electrode systems are common with recording via 8, 10, 16, 20 or 32 channels being typical (Figure 105). The amplifiers are high impedance ( $12\text{ M}\Omega$ ), with a variable high gain, high common mode rejection ratio (100 dB), differential input and low noise. Variable band pass filters with 50 or 60 Hz notch filters are used. The electrode input combinations are electronically switchable. Driver amplifiers provide an output to a chart recorder in real time. The signal is also digitised for further analysis.

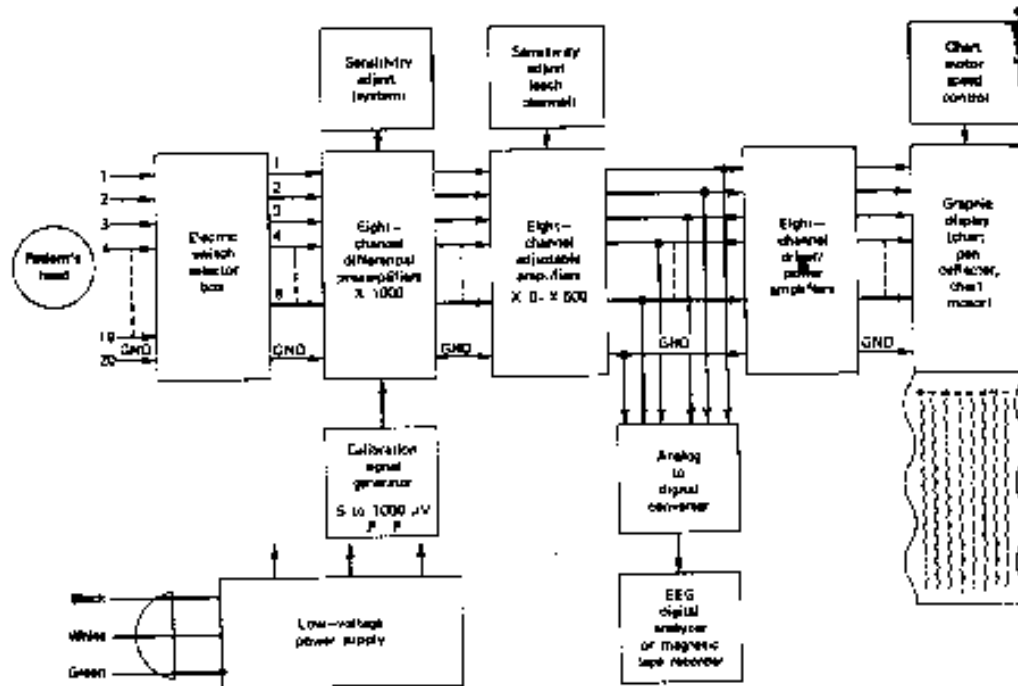


Figure 105 Block diagram of an 8-channel EEG recording system.

EEG recording systems are frequently used with peripheral nerve, auditory and visual stimulation to produce “evoked potentials” (Figure 106). Nerve stimulation is via needle electrodes inserted through the skin adjacent to the nerve or via skin electrodes. Recordings may be made in other nerves as well as the EEG. Auditory stimulation is made with “clicks” or bursts of single frequency tones. Visual stimulation is via fixed or moving patterns, usually checkerboard, displayed on a monitor for the patient. The response is of very low amplitude and is typically lost in the pseudo-random patterns from the rest of the brain. To overcome this problem, the stimulus is repeated many times (typically 128) in quick succession and the responses summed and averaged by computer (Figure 107).

The EEG is sometimes recorded when the patient is asleep or performing normal daily tasks. In order not to disturb the patient, only the electrodes, preamplifiers and stimulators are with the patient. Telemetry is used to communicate with the rest of the equipment in a different room (Figure 108).

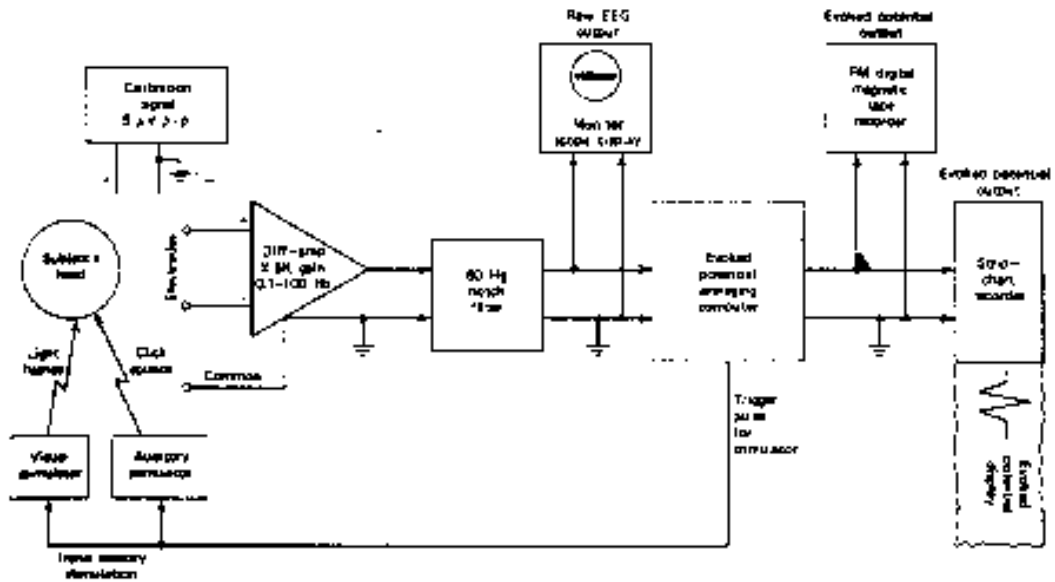


Figure 106 Block diagram of a visual and auditory evoked potential system.

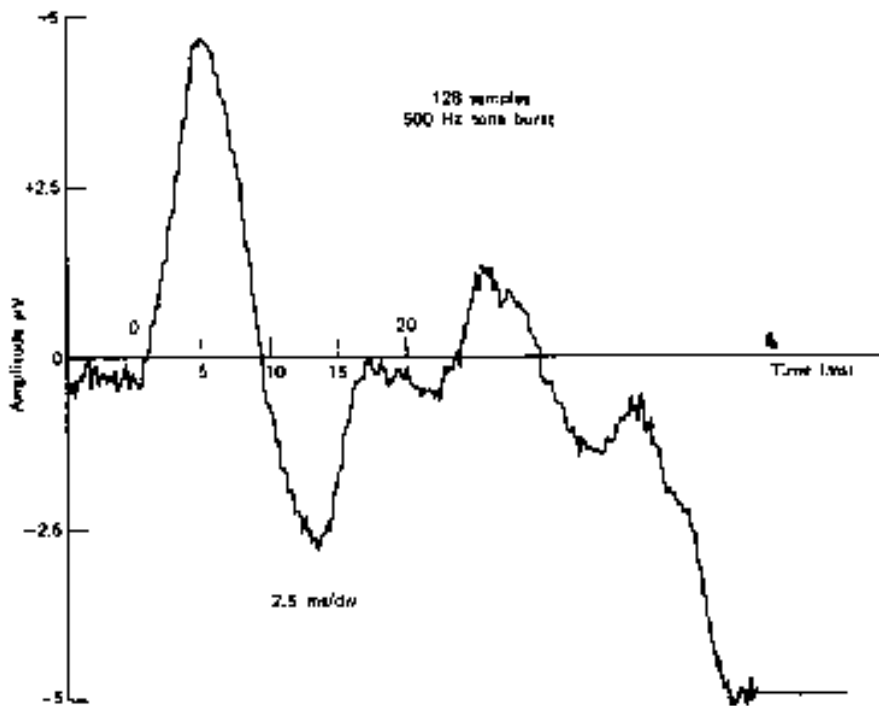


Figure 107 Auditory (tone burst) evoked potential from a 22 year old male.

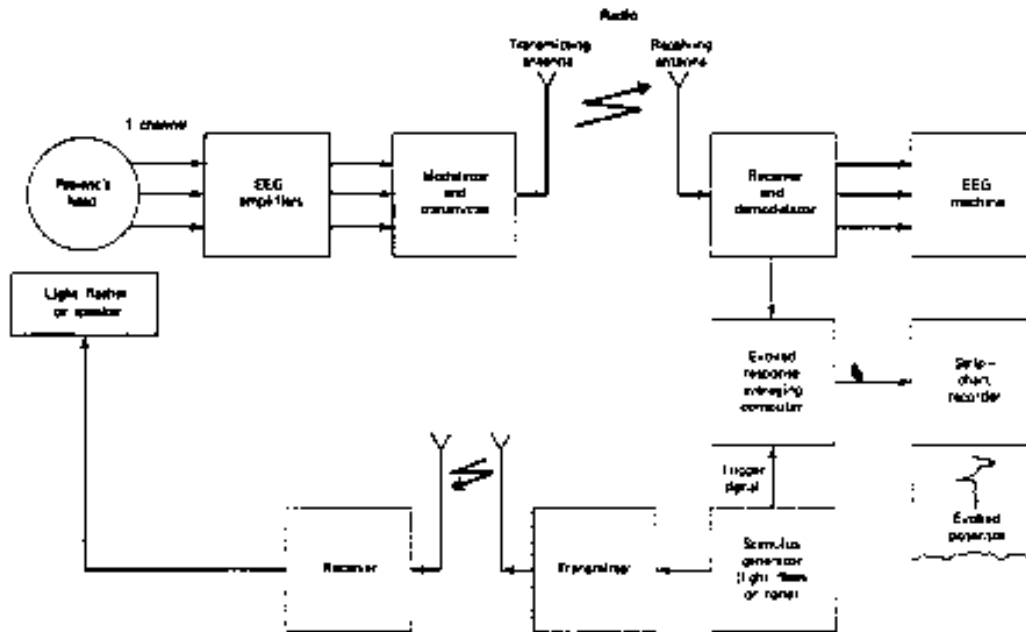


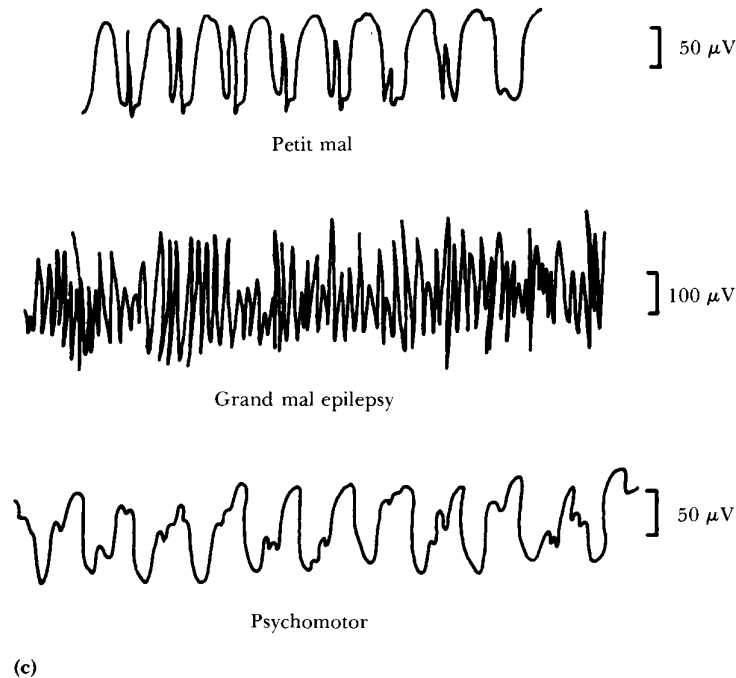
Figure 108 Block diagram of an EEG telemetry system.

### Abnormal EEG

Abnormalities may be found in organic brain damage, tumours, infarcts, haemorrhages, demyelinating diseases, such as multiple sclerosis (MS), after viral encephalitis and in epilepsy. Generally tumours, infarcts and haemorrhages are better detected by other means, so the EEG is not used as a first option for diagnosis.

The EEG is the main diagnostic tool for epilepsy. Epilepsy is characterised by uncontrolled excessive activity in all or part of the brain. If the activity is above a threshold, the patient will exhibit symptoms; such as convulsive contractions of the muscles; “absences” where the patient is unaware of their surroundings and does not respond to stimuli for a period of seconds or minutes; or abnormal behaviour.

Epilepsy may be partial or general. In general epilepsy the patient becomes unconscious, the patient has a general *tonic* contraction of all their muscles, followed by alternating *clonic* contractions. This is also known as *grand mal* epilepsy with *tonic-clonic convulsions*. Following the seizure, which may last from a few seconds to four minutes, the patient is in a stupor for a minute to a day or more. The EEG shows large amplitude, low frequency spikes from all parts of the brain during grand mal (Figure 109). In between seizures, the patient may have a localised area of the brain showing large amplitude, low frequency spikes. This region is known as the focus.



**Figure 109 Typical waveforms in three types of epilepsy.**

Another form of epilepsy, formerly known as *petit mal*, occurs as myoclonic and absence epilepsy. In the myoclonic the burst of neuron discharges last only a fraction of a second and there is a single, violent muscular jerk. In the absence form, there is a loss of consciousness lasting for a few seconds, sometimes associated with muscle twitching and eye blinking.

Partial epilepsy can involve any part of the brain. It usually arises from an area of brain that is damaged or scarred or has some other abnormality compressing the brain, such as a tumour. Depending on the site of the focus, it can cause a wave of contractions spreading over the body, a short period of amnesia only, an attack of rage or fear, or a repetitive movement. The patient may or may not be aware of the attack but is unable to control it.

Stimulating the eyes with fixed or moving patterns can show defects in pathways concerned with vision, or point to epileptic foci in those pathways. If a repetitive pattern at the right frequency is displayed before the patient, focal or petit mal epilepsy may be provoked and recorded. Comparison of timing along the optic pathways between the right and left sides can show damage on one side causing delay in signals travelling from the retina to the occipital cortex at the back of the brain, where vision is consciously perceived. This is seen in viral optic neuritis, MS and vascular lesions (eg aneurisms: ballooning out of a defect in the wall of an artery) (Figures 110 and 111).



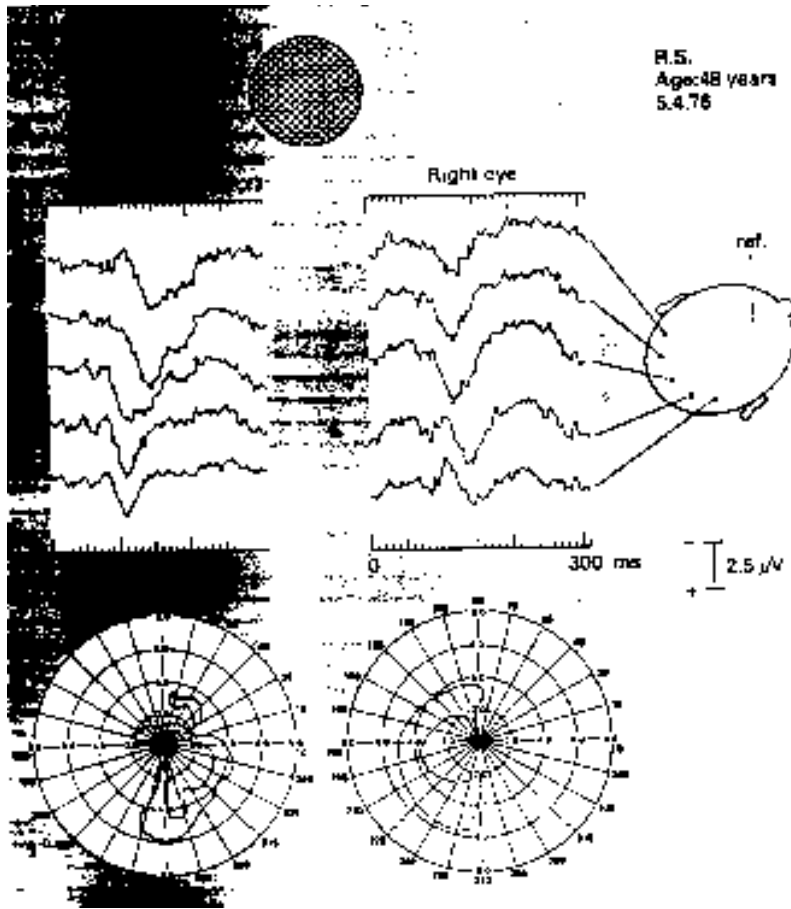
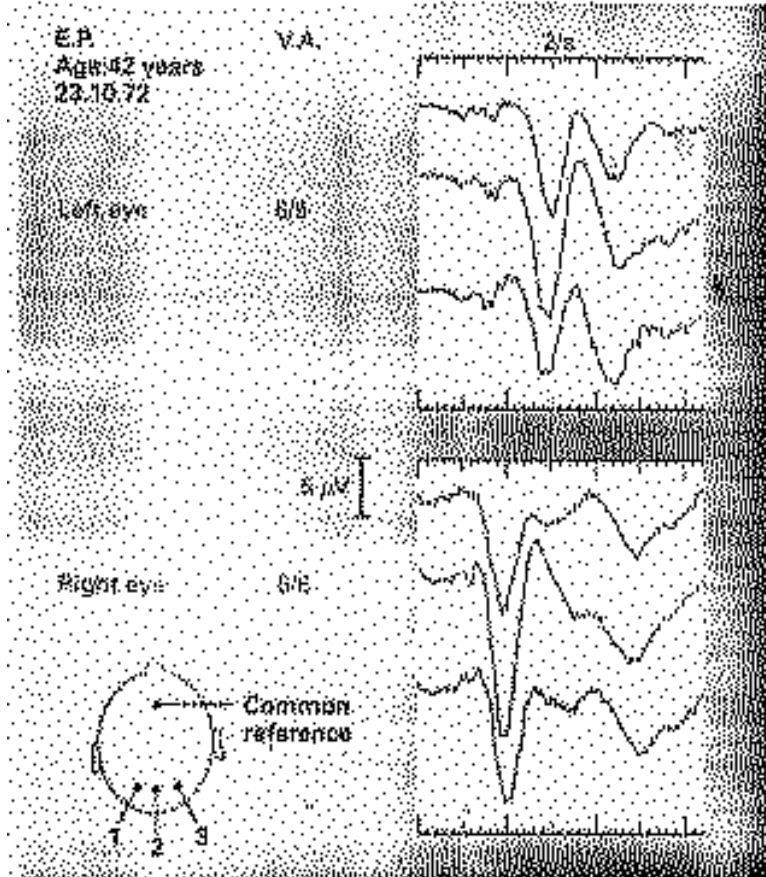


Figure 110 Pattern reversal responses to a full-field checkerboard stimulus (top) for each eye from a 26 year old man with an incomplete homonymous hemianopia (one-sided blindness), associated with a vascular lesion of the posterior cerebral circulation (stroke) in the left cerebral hemisphere. The response shows an “uncrossed asymmetry”, the P100 ms component being seen at the electrodes in the midline and ipsilateral (same side) to the preserved left half field. The bottom diagrams are the visual fields for each eye.



**Figure 111** Pattern reversal response from each eye of a patient recorded one month after an attack of left optic viral neuritis. The response from the right eye is of normal waveform and latency (delay), the major positive component (P100 ms) being clearly seen, preceded and followed by the smaller negative components (N75 ms and N45 ms). The response from the affected left eye is delayed by 45 ms. Time scale 10, 50 and 100 ms.

Recording from the temporal lobe of the cortex, where hearing is perceived, or the adjacent brain stem, while stimulating the ear with sound can detect defects in those pathways. The advantage of this technique is that it does not require the cooperation of the patient, so that infants may be tested for deafness (Figure 112).

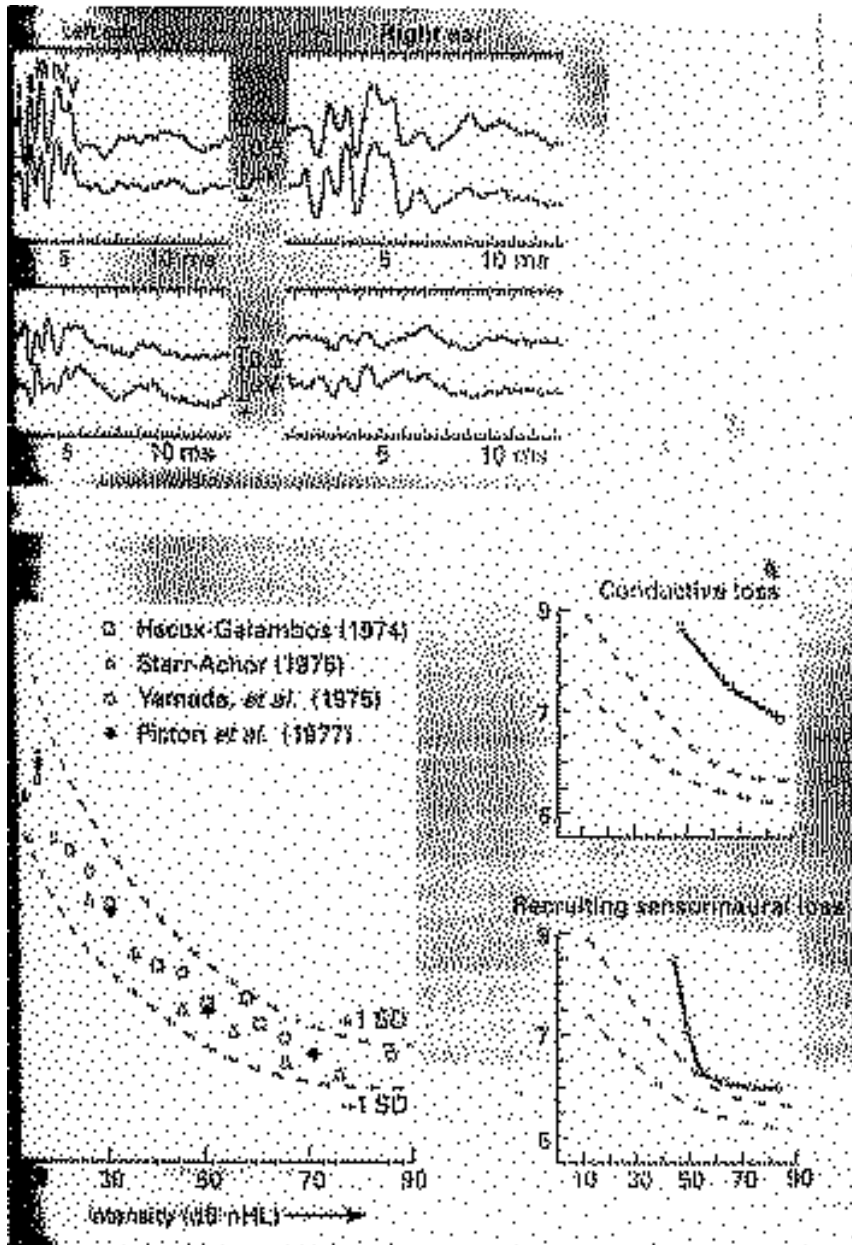
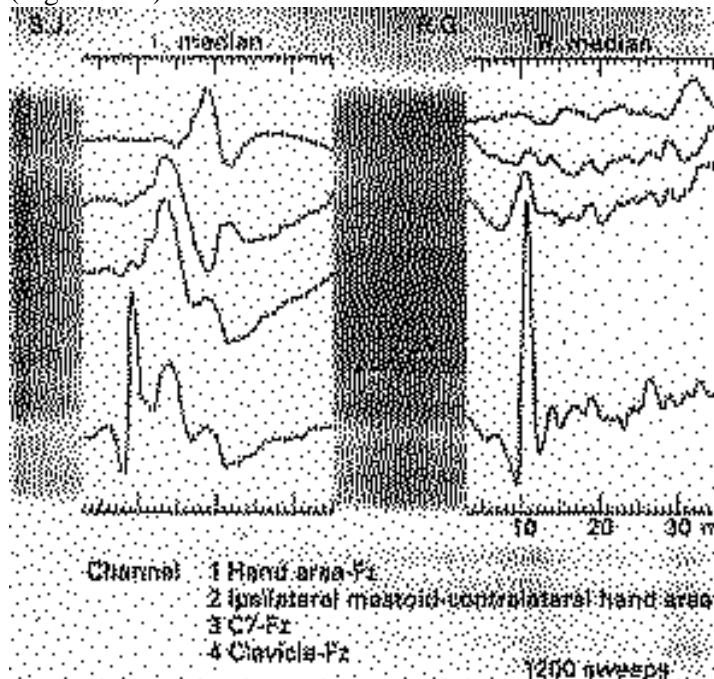


Figure 112 Evoked auditory potentials (top 4 diagrams) for normal left and partly deaf right ear. The bottom three diagrams show normal hearing test range on the left, as found from other research laboratories. The two right lower diagrams are hearing measurements for the patient's right ear showing some of the deafness is in the hearing nerve and/or pathway through the brain (recruiting sensorineural loss) and part of the deafness is due to sound conduction problems in the middle ear (conductive loss).

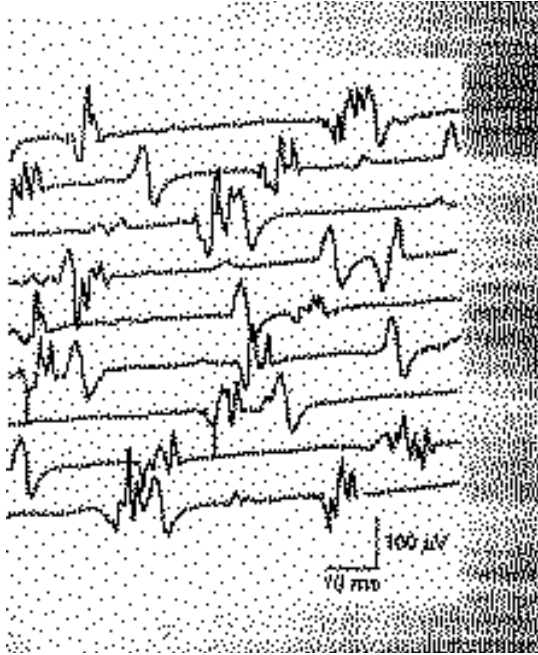
Electroneurograms (ENG), recordings made from nerves while stimulating the nerves by electrical pulses or other means, may be used in conjunction with an EEG to test for peripheral and central nerve defects. Peripheral nerve defects may be found in vitamin deficiency, poisoning by alcohol or other substances or after injury. Central nerve defects may be found in demyelinating diseases, such as MS. Defects are shown by the lack of a response or the delay in response to a stimulus, which may be

measured at any point along the pathway in the peripheral or central nervous system (Figure 113).



**Figure 113** Somatosensory (muscle and sensation) responses to electrical stimulation of the median nerve in the wrist in a healthy subject (left record) and in a patient suffering multiple sclerosis (right record). The contralateral Rolandic response (reflex muscle movement in the opposite arm) (top trace) shows a well-marked early cortical component (N20 ms) in the normal person. The component is very greatly delayed in the patient with MS, occurring with a latency (delay) of about 32 ms. The peripheral N9 ms component from the brachial plexus (nerve branches under the armpit), recorded over the clavicle (collar bone) (bottom traces) are normal for both records. The cervical response (recording in the neck received from the spinal chord) in the left record shows a prominent N13 ms component preceded by a smaller N10ms and an even smaller N9 ms. The N14 component from the brain stem is best seen in the mastoid recording (just behind the ear, second trace), where it appears as a prolongation of the N13 ms component. Apart from N9, none of the components of the “electrospinogram” are seen in the record from the patient with MS. The traces were obtained by repeating the stimulation and recording 1200 times and averaging the recordings.

Electromyograms (EMG), recordings made from muscle fibres, may be used to assess muscle disease or defects in the enervation of muscles, such as occurs after trauma to their nerve supply. If the nerve supply is partially lost, instead of continuous patterns of muscle fibre action potentials being seen, only occasional ones are recorded. When a muscle is re-enervated after trauma to the nerve supply, some muscle fibres will take their supply from adjacent intact nerve fibres if the original nerve fibres fail to grow back. This causes muscle action potentials to occur in groups, instead of a more continuous spread (Figure 114).



**Figure 114 Motor unit (muscle fibre groups) on weak effort. Some of the spikes are of simple form, others are polyphasic. The recording is taken from the 1st dorsal interosseous muscle of the hand of a patient with a chronic lesion (damage) of the ulnar nerve at the elbow. An increased frequency of polyphasic potentials compared to normal indicates that denervated muscle fibres have been incorporated into surviving motor fibre units by collateral sprouting of healthy nerve fibres.**

### *Future Developments*

Attempts have been made to produce three-dimensional pictures of the brain from the EEG recordings. However this has not been successful as the recordings deep within the brain tend to be swamped by those closer to the surface and the brain and surrounding head are not homogeneous volume conductors, so that it is not possible to localise potentials accurately.

The electrical currents associated with action potentials produce very weak magnetic fields. Typically the magnetic field of an alpha wave 5 cm from the scalp is  $0.1 \mu\text{T}$ , whereas the earth's magnetic field is  $\sim 50 \mu\text{T}$ . The use of superconducting quantum interference devices (SQUID) has enabled these fields to be recorded from the brain with the patient in a magnetically shielded room. These recordings are known as a magnetoencephalogram (MEG). The head is a uniform magnetic medium so that it is possible to construct a three-dimensional image of the brain, or a series of two-dimensional slices, in the same way as a CT scan. It is not necessary for any SQUID to be in contact with the patient. To date these images have been crude as it has not been possible to use sufficient sensors to obtain a high resolution image. However they have enabled defects in brain regional function to be discovered that was not previously possible. At present these devices are not in general use because of their cost.