# Normal Electroencephalogram

**Chailerd Pichitpornchai, M.D., Ph.D.**
*Department of Physiology, Faculty of Medicine Siriraj Hospital, Mahidol University, Bangkok 10700, Thailand.*

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## Definition and Source of EEG

Electroencephalogram (EEG) is the record obtained by using an electroencephalograph which is a system or equipment for recording the continuous electrical activities or potentials of the brain derived from surface electrodes attached to the scalp. Electroencephalography is the registration of the electrical potentials recorded by an electroencephalograph.

The brain is composed of millions of neurons which are excitable tissues capable of undergoing excitation in response to an adequate stimulus. At rest, a neuron generates a resting membrane potential. This membrane potential is established by the balanced influx and efflux of cations and anions across the cell membrane influenced by electrochemical gradients and a $Na^+$-$K^+$ pump. When the neuron, is excited or stimulated by another presynaptic neuron's axon terminal, neurotransmitters are released from the presynaptic membrane into the synaptic junction, bound to receptors on the postsynaptic dendrite or membrane of the stimulated neuron. This results in compensatory currents in the extracellular space that are responsible for the generation of EEG voltages. The neuron then generates an action potential propagating through its axon. It is noted that the EEG is not sensitive to axonal action potentials.

The surface or scalp EEG measurement is a kind of extracellular recording of neuronal electrical activities recorded via surface electrodes attached to the scalp, therefore, it is not possible to identify each individual single dendritic potential. Instead, surface EEG is the summation of the synchronous activity of thousands of neurons that line the surface of the hemispheres and have a similar spatial orientation, parallel to the radial arrangement of apical dendrites in the cortex. Currents that are perpendicular to the scalp are not picked up by the EEG. The intensity and patterns of the electrical activity are determined to a great extent by the overall level of excitation of the brain resulting from sleep, wakefulness, and brain diseases such as epilepsy and some psychoses.

Due to the fact that voltage fields fall off with the fourth power of the radius, the currents from those neurons located near the skull are easier and stronger to be recorded than currents from those situated deeper in the brain. This results in a typical adult human EEG signal of about 10-100 μV in amplitude. Surface EEG has a low spatial resolution because of the filtering characteristics of the skull and scalp. Therefore, a bigger amplitude of about 10-20 mV and a higher spatial resolution can be achieved by using intracranial EEG (icEEG), subdural EEG (sdEEG), electrocorticography (ECoG) or intra-operative EEG monitoring, which is measured from patients undergoing a brain surgery.

## How to record EEG

Practically, in scalp EEG, the recording is obtained by rubbing skin-prep on the scalp in order to reduce impedance caused by keratin or dead skin cells, applying with a conductive gel or paste, and placing surface electrodes on the scalp. Each electrode attached to an individual wire is then secured on the scalp and connected to a junction box and an electroencephalograph.

The International 10-20 system is one of the most commonly used electrode locations on the scalp for clinical and research applications. The standard set of electrodes for adults are composed of 19 recording electrodes and one ground electrode. The electrode placements are prefrontal or frontopolar (Fp1 and Fp2), frontal (Fz, F3, F4, F7 and F8), central or precentral (Cz, C3 and C4), parietal (Pz, P3 and P4), occipital (O1 and O2), temporal (T3, T4, T5 and T6) and auricular (A1 and A2 – ground) areas (Fig 1). The subscript is either the letter z, indicating zero or midline placement, or a number, indicating lateral placement. Odd and even numbers refer to electrodes placed on the left and right, respectively. A smaller number of electrodes are used in neonates. Most of the EEG recording systems are now digitally recorded by using an analog-to-digital converter, typically sampled at 256-512 Hz for clinical use and up to 10 kHz for some research use. EEG caps or nets providing a high density array of electrodes are usually used for research applications.

Normally, a scalp EEG recording for clinical use lasts for 20-40 minutes. There are several activation procedures applied to the patient in order to evoke different brain activities, such as eye closures, hyperventilation, intermittent photic stimulation with a strobe light, and sleep. Inter-ictal discharges, abnormal activities resulting from brain irritability that shows a possible predisposition to epileptic seizures, are specially looked for in patients with suspected or known cases of epilepsy. Video-EEG monitoring and continuous EEG monitoring are sometimes necessary for some epileptic patients admitted to the hospital in order to detect the abnormal discharges occur during seizures.

## Limitation of EEG

Although EEG can give a continuous electrical activity

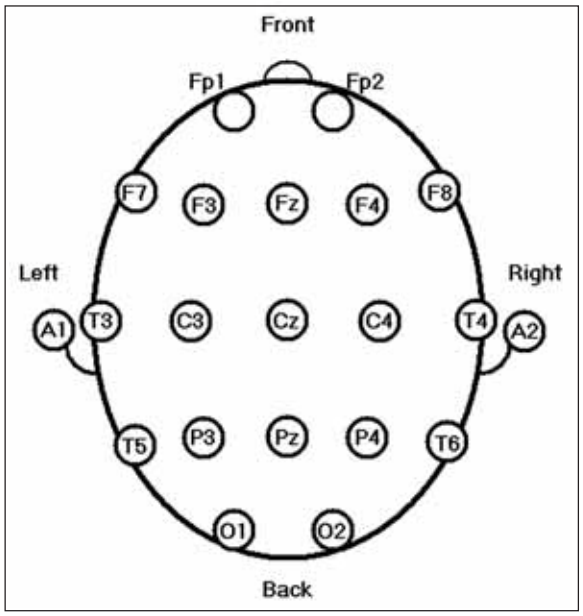


**Fig 1.** Placement of recording electrodes in the International 10-20 System.

of the brain, there are some limitations of EEG. Firstly, the most important one is its poor spatial resolution. EEG is most sensitive to a particular set of post-synaptic potentials, i.e. those which are generated in superficial layers of the cortex, on the crests of gyri directly abutting the skull and radial to the skull. However, those dendrites which are situated deeper in the cortex, inside the sulci, in midline, or deep structures (such as the cingulate gyrus or hippocampus), or those which produce currents which are tangential to the skull have far less contribution to the EEG signal. Secondly, the meninges, cerebrospinal fluid and skull obscure the EEG signal. Thirdly, it is mathematically impossible to reconstruct a unique intercranial current source for a given EEG signal, as some currents produce potentials that cancel each other out. This is referred to as the inverse problem. However, much work has been done to produce remarkably good estimates of, at least, a localized electric dipole that represents the recorded currents. Fourthly, scalp electrode recording may show extracerebral potential changes produced either by biological activity such as saccadic eye movements, heart beats, or scalp muscle contraction. Lastly, EEG artifacts can be caused by eye movements, muscle activities, heart beats, respirations, and faults from the recording system ranging from electrode placements for the electroencephalograph.

## EEG Activity

In order for the EEG reader to be able to analyze EEG, one needs to distinguish wave form, repetition, frequency, amplitude, distribution, phase relation, timing, persistence, and reactivity. However, in practical points of view, the EEGs are typically described in terms of rhythmic activity and transients. The rhythmic activity is divided into bands by frequency. The recorded frequencies falls in the range of 1-50 Hz (normally 1-20 Hz) of about 10-100 μV in amplitude (normally 10-50 μV). According to rhythmic activity, the EEGs can be divided into 4 major wave forms, namely alpha, beta, theta, and delta.

**Alpha wave** or alpha rhythm has the frequency of 8-13 Hz. Normally, it can be easily recorded from the posterior regions of the head (occipital cortex or visual area) with a bigger amplitude on the dominant side of the

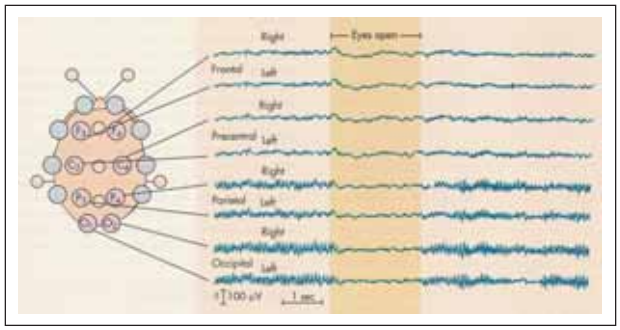

**Fig 2.** EEG recordings from eight sites on the scalp. In the resting condition an alpha rhythm is prominent over the occipital and parietal lobes. When the eyes are opened, the alpha rhythm is blocked and replaced by a beta rhythm (Berne & Levy, 2000).

brain. The alpha wave can be brought about by asking the patient to stay awake, relax, and close the eyes. Alpha rhythm is mostly found in calm or meditating people. Mental exertion or attention, or opening the eyes will attenuate the alpha rhythm. This brain activity in now referred to as "posterior alpha rhythm", or "posterior basic rhythm" or "posterior dominant rhythm". This rhythm is found slower than 8 Hz in young children.

**Beta wave** has a frequency range of 13-35 Hz and a small amplitude of 5-10 μV, not exceeding 30 μV. It is most evident frontally with a frequency range of 35-40 Hz. The beta wave can also be found at different areas of the scalp at different frequencies of 20-30 Hz at the central area, and 14-19 Hz at the occipital area. A beta wave with a low amplitude, and with multiple and varying frequencies is often associated with active mental exertion, busy or anxious thinking, and active concentration. The opening of the eyes results in changing of an alpha wave to a beta wave. The beta wave may be absent or attenuated in areas of cortical damage. Beta rhythm with a dominant set of frequencies can be found associated with various pathologies and drug effects, especially benzodiazepines.

**Theta wave** has a frequency range of 4-7.5 Hz. It is hardly seen in healthy adults staying awake, but it may be seen in drowsiness or arousal in older children and adults, and in meditating people. Excess theta in the elderly represents abnormal activity.

**Delta wave** is the frequency range up to 3 Hz and tends to have the highest amplitude. It is seen normally in adults in slow wave sleep, and in babies. Theta wave and delta wave can be found in several abnormalities, for examples, focal subcortical lesions, diffuse disorders or metabolic encephalopathy, deep midline disorders, and in some instances of hydrocephalus.

In addition to the major wave forms described above, there are some other waves found occasionally, such as Mu rhythm, lambda wave, vertex wave (V wave), and K-complex.

The **Mu rhythm** is an alpha-range activity that is recorded from the sensorimotor cortex area. It characteristically attenuates with movement of the contralateral arm or even by the mental imagery of movement of the contralateral arm. The **Lambda wave** is a positive potential recorded from the occipital area. It is associated with eye openings or eye movements. **The Vertex** wave can be found in frontal and central areas. It is associated with sleep stage I, and sometimes appears in response to a sensory stimulus. The **K-complex** is a slow wave resembling vertex wave in distribution and reacting to sensory stimuli, such as sound stimulus. The **K-complex** is usually longer and less

sharp than the vertex wave and is often preceded or followed by a positive wave. This biphasic or triphasic wave is often followed by a sleep spindle.

## Normal EEG

An EEG is usually considered normal because of a lack of abnormal patterns at the time of recording, instead of the presence of normal patterns. However, a normal EEG does not guarantee the absence of cerebral pathology because not all abnormalities of brain structure and function produce abnormal EEG patterns. To interpret EEG correctly, the EEG reader has to recognize the major features of the normal EEG at different ages and sleep-wakefulness states, and to distinguish them from abnormal components by using a set of precise electrographic elements. The normal EEGs can be categorized into 3 classes according to age from premature up to the age of 19 years, adults aged between 20-60 years, and adults above the age of 60 years.

It is worth emphasizing that a normal EEG does not always mean normal brain function. Most acute, severe and large abnormalities of the brain are likely to result in an abnormal EEG. Normal EEGs can be seen in some cases of long-standing, mild and small cerebral abnormalities. Lesions far from the recording electrodes, such as a small infarct at the internal capsule or hippocampus, may result in a catastrophic hemiplegia, but no EEG abnormalities are seen. In contrast, a large infarct located near the recording electrodes may result in EEG changes lasting for a few weeks or months, but the EEG may then become normal even though the neurological deficit still persists. Senile dementia or other slowly progressive and widespread brain diseases may reveal a normal EEG for a long period before becoming cerebral atrophy and mental deterioration. Typical cases of epilepsy are usually not detected by EEG recording because the epileptogenic focus does not fire during recording.

## Normal sleep EEG

The sleep EEG of adults shows less variation of patterns between individuals than does the waking EEG. Normal sleep EEG is composed of slow waves, sleep spindles, positive occipital sharp transients of sleep (POSTs), vertex sharp transients (V waves) and K-complexes. EEG artifacts of electrical activities from eye movements and muscle activity are usually picked up in sleep EEG.

Sleep stages can be divided into stage W, stage I-IV of slow waves, and stage of rapid eye movement (REM). These stages can be distinguished by EEG patterns consisting of different combinations of electrographic elements. Stage W, representing wakefulness at the transition to drowsiness, may show some slowing and remarkable alpha rhythm at the posterior electrodes. Beta rhythms may be present and continue into stage I of sleep and they are remarkably prominent in sedatives-induced sleep.

The EEG of sleep stages is shown in the left panel of Figure 3 and is briefly described as follows. The alpha rhythms in sleep stage W disappear in sleep stage I, instead, slow waves of 2-7 Hz begin. Slow waves during this light stage of sleep may be difficult to distinguish from abnormal generalized slow waves occurring during wakefulness, although the slow waves of drowsiness can be identified by the following deeper sleep stages EEG. Stage II is characterized by the presence of sleep spindles of at least half a second in duration, K-complexes or both. POSTs often persist in stage II. Stage III is characterized by the presence of a moderate amount of very slow waves

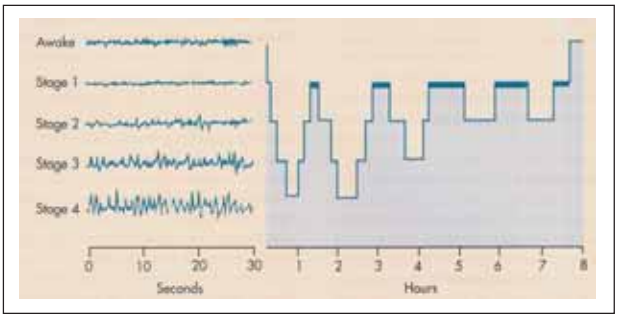


**Fig 3.** Stages of sleep and changes during the night. Left panel shows EEG recordings during the waking state and progressively deeper levels of non-REM sleep. The EEG in REM sleep would resemble that shown for the awake individual. Right panel shows different sleep stages experienced during a typical night for a young adult. The bars represent periods of REM sleep (Berne & Levy, 2000).

(2 Hz or less) of high amplitude (75 μV or more). K-complexes are often present, and POSTs can usually be distinguished. Stage IV is characterized by the presence of slower wave activities than in stage III. They occupy more than half of the recording time. Stage REM is characterized by low voltage EEG patterns, rapid eye movements, and generally reduced muscle activity. Additional placements of electrodes near the eyes can be applied in order to specially monitor rapid eye movements. REM sleep has characteristics of both very light and very deep sleep and is associated with dreaming. Sleep cycles are characteristic sequences of sleep stages which are best studied in all-night sleep recordings (Fig 3 - right panel).

## Abnormal EEG

Most of the time, abnormal EEG patterns indicate abnormal brain functions, although, there are some instances that abnormal EEG patterns do not represent any evidence of brain diseases. For example, an EEG of unusually low amplitude may occur in about 5-10% of normal persons after the age of 20 years. This same pattern may be observed in patients with mild forms of diseases indicating mild cerebral abnormalities. Therefore, follow-up clinical manifestation and EEG recordings are needed in order not to overlook the possibility of such mild cerebral abnormalities.

The EEG abnormalities can be divided into several basic abnormal EEG patterns, for examples, epileptiform activity (localized, generalized, and special epileptiform activities), slow waves (localized, generalized asynchronous, and bilaterally synchronous slow waves), amplitude abnormalities (localized, and generalized amplitude changes), and deviations from normal patterns. These abnormal EEG patterns will not be described in details here because this article is about normal EEG.

## Clinical and research application

The advantage of using EEG is that EEG is a non-invasive investigation with high temporal resolution looking into the changes of the brain's neuronal electrical activity on a millisecond time scale. EEG has a low spatial resolution when it is compared to high spatial resolution data recording techniques, for examples, functional magnetic resonance (fMRI) or positron emission tomography (PET). However, these techniques have a poorer temporal resolution, ranging from several seconds to minutes, and this results in a different time course when comparing the actual brain

activity with the recorded data set. Another point of advantage of EEG is that it looks directly into the brain's electrical activity, whereas fMRI and PET look into changes in blood flow and metabolic activity, respectively, which are indirect markers of brain electrical activity.

The clinical applications of EEG are to identify epileptic seizures from other types of spells, such as psychogenic non-epileptic seizures, fainting, sub-cortical movement disorders and migraine variants. It can be used to characterize seizures for the purposes of treatment, and to localize the region of brain from which a seizure originates to work-out for possible seizure surgery. Besides, EEG can be used to monitor for non-convulsive seizures or non-convulsive status epilepticus, to differentiate organic encephalopathy or delirium from primary psychiatric syndromes such as catatonia, to monitor depth of anesthesia, and to serve as an adjunct test of coma and brain death.

The research applications of EEG are to identify staging of sleep in sleep research, and to provide a cognitive research tool by the application of an event-related potential (ERP) technique. In most ERP paradigms, two or more stimuli are applied to the patient and an EEG is recorded when the stimulus-response is going on. The ERP is obtained by averaging the EEG signal from each of the trials within a certain condition. Averages from one stimulus-response condition can then be compared to averages from the other stimulus-response condition. The ERP is agreat contribution to neurobehavioral science studies, as well as cognitive research such as learning and memory function studies. In some research, EEG is combined with fMRI or PET scan in order to complement real-time functional data to the anatomical data of the brain.

In conclusion, for clinical application, EEG is a non-invasive investigation of choice when real-time electrical activity of cortical neurons is needed to evaluate the function of the brain, and to help identify several functional abnormalities of the brain, to name just a few, epilepsy, cerebral cortical lesions, and brain death. Continuous all-night sleep recordings of EEG and provision of ERP technique are invaluable to sleep research and neurobehavioral science research, such as cognitive study, respectively.

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