EE 791
EEG -1

Although there are many methods of recording the activity of neurons in the brain, the one we shall concentrate on is the scalp recorded potential called EEG (Electroencephalogram). This is the most used method of recording brain activity because it is non-invasive.

Brain Wave Recordings

- Recorded extra-cellularly from scalp (EEG)
- Recorded from extra-cellularly from surface of cortex (ECOG)
- Recorded extra-cellularly from deep structures (electroneurogram)

Structure of the Brain

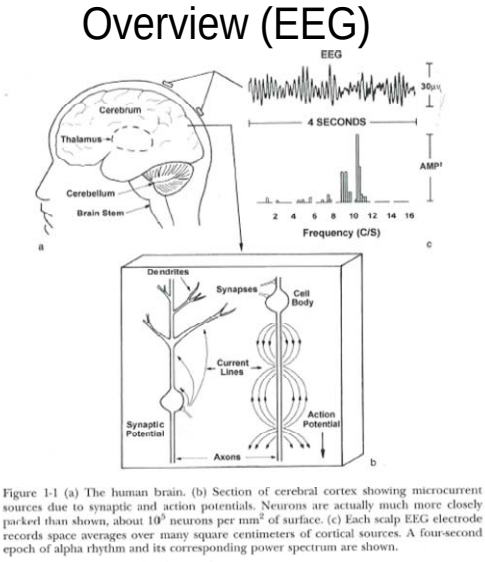


Figure 1-1 (a) The human brain. (b) Section of cerebral cortex showing microcurrent sources due to synaptic and action potentials. Neurons are actually much more closely packed than shown, about 10^5 neurons per mm^2 of surface. (c) Each scalp EEG electrode records space averages over many square centimeters of cortical sources. A four-second epoch of alpha rhythm and its corresponding power spectrum are shown.

From Nunez and Srinivasan 2006

The brain has several very well defined areas the largest being the brainstem (brain segment on top of the spinal cord which is the most primitive part of the brain in that it

regulates the basic life functions such as breathing); the cerebellum lying low down behind the brainstem which is involved with integrating signals such as regulating balance but is also used for other functions; the thalamus which is an integrating centre accepting and sending signals to other parts of the brain much as a railroad switchyard, as well as providing some of the inhibition or suppression of neural activity; and the largest area, the cerebrum which provides motor, sensory and many other functions.

Cortical Contributions

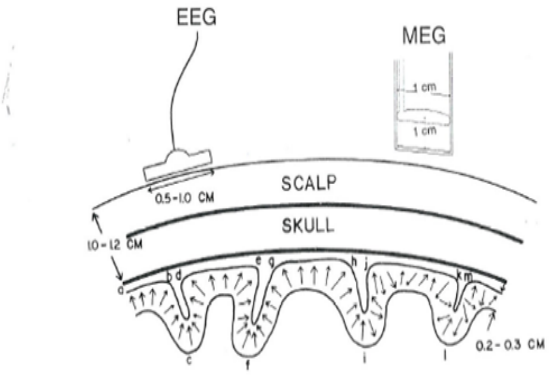


Figure 2-3 Neocortical sources can be generally pictured as *dipole layers* (or "dipole sheets," in and out of cortical fissures and sulci) with mesosource strength varying as a function of cortical location. EEG is most sensitive to correlated dipole layer in gyri (regions ab, de, gh), less sensitive to correlated dipole layer in sulcus (region hi), and insensitive to opposing dipole layer in sulci (regions bcd, efg) and random layer (region ijklm). MEG is most sensitive to correlated and minimally apposed dipole layer (hi) and much less sensitive to all other sources shown, which are opposing, random, or radial dipoles. Modified version reproduced with permission from Nunez (1995).

From Nunez and Srinivasan 2006

The most interesting segment of the cerebrum for our purposes since it is the origin of scalp potentials is the cerebral cortex (neocortex in mammals) which is a layer of neurons 2 to 5 mm thick which is folded with the folds called gyri (singular gyrus) with shallow grooves called sulci and deeper grooves called fissures (slide 4). The neurons in the cortex are highly organized in vertical layers (I to VI) with the dendrites or input branches at the top and the output axons leading downward. The dendrites are mostly organized horizontally and these contain the input connections or synapses (excitatory and inhibitory) from other neurons (up to 100K for a single neuron). The total surface area of the cortex is 1600 to 4000 cm^2 and contains about 10^{10} neurons. We can view the neuron as a multi-input, single output system which temporally and spatially integrates all the inputs in a complex manner and generates an output pulse or action potential through the axon if the internal cell potential in the cell body or soma passes a threshold level. The entire inter-cell communication system can be viewed as a pulse communication system with no information in the action potential shape, amplitude or duration just its presence and time of occurrence.

Excitatory synapses raise the internal potential of the neuron (resting internal potential could be – 60 mv) towards the firing threshold thus raising the excitation level of the cell by opening Na^+ gates in the cell membrane resulting in inward positive current flow (current sink) and an excitatory post synaptic potential (EPSP). Inhibitory synapses

create an inhibitory post synaptic potential (IPSP) by opening Cl^- gates resulting in a positive current source. This decreases the internal cell potential making the cell less excited. It must be stressed that this synaptic activity is continuous over time and may or may not result in the cell firing. The current sources and sinks can viewed as current dipoles. Because of the impedances of the biological tissues and the distance between the neurons and the surface electrodes, individual action potentials or synaptic current sinks and sources will not produce a measurable signal on the scalp. Rather we need many coherent sources to be summated at the scalp before an appreciable brain signal can be detected. Action potentials which are in the bandwidth of 100's of Hz to 15 KHz do not therefore contribute to the scalp EEG. However, because of the highly organized structure of the dendrites from many neurons in the cortex and the immense number of synapses for even a relatively small population of neurons, the synaptic source and sink current dipoles for a group of neurons, when aligned and occurring sufficiently coherently will give rise to measurable scalp potentials. In biological tissue we can assume that the distribution of current sources and sinks can be approximated by a dipole if we are 3 to 4 times the diameter of the source region away from it. Of course the field resulting from these dipoles attenuates as $1/r^2$. The aggregate dipole bandwidths are much lower in frequency than for the action potentials and the resulting scalp potentials have a bandwidth in the sub Hz to tens of Hz range. EEG provides a large scale short-time measure of the modulations of the synaptic fields about their background levels.

EEG Subfields

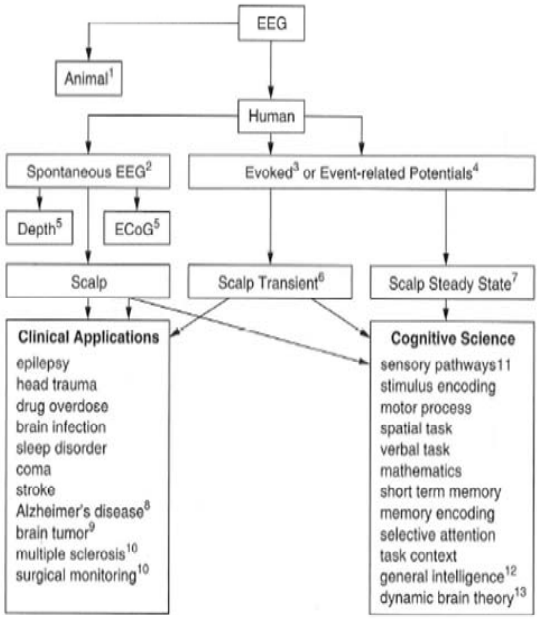


Figure 1-3 Common relationships between EEG subfields. Clinical applications are mostly related to neurological diseases. EEG research is carried out by neurologists, cognitive neuroscientists, physicists, and engineers who have a special interest in EEG. See text for a discussion of numbered superscripts. Reproduced with permission from Nunez (2002).

From Nunez and Srinivasan 2006

The above figure shows the application areas of EEG both clinical and research. EEG has gained a new importance as signal processing and modeling techniques become more sophisticated and faster computationally on modern PC's. Invasive techniques such as ECoG and depth recordings are mainly done on animals now. In the past neurosurgeons would use these techniques to determine very localized neural activities in patients, especially epilepsy patients, in curiosity driven research. However, this is hardly ever done in recent times because of the much higher ethical standards required currently for human invasive recordings. They are still allowed in clinical research or operative investigations if it can be shown that the patient could directly benefit, such as identification of the seizure area in the brain prior to surgical excision or the implantation of deep brain stimulators (in Parkinsonism in the thalamus) or implantable brain 'defibrillators" in epilepsy.

Neuronal Connections

Neurons in the cortex are highly interconnected over short and long distances (corticocortical fibres). A much smaller number go from and to the thalamus (few %). Most connections within each hemisphere are short with axons < 1 mm but long distance pathways exist (10^{10} fibres) in the 1 to 15 cm also exist as shown below. The two hemispheres are connected through the corpus callosum with approximately 10^{8} fibres

Cortical Fibres

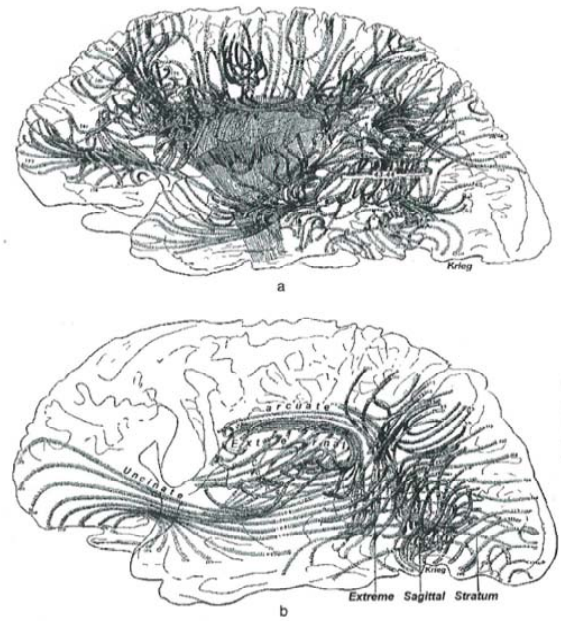


Figure 1-2 (a) Some of the superficial corticocortical fibers of the lateral aspect of the cerebrum obtained by dissection. (b) A few of the deeper corticocortical fibers of the lateral aspect of the cerebrum. The total number of corticocortical fibers is roughly 10^{10}, that is, for every fiber shown here, about 100 million are not shown. Reproduced with permission from Krieg (1963, 1973).

From Nunez and Srinivasan 2006

Transmission times for corticocortical axons could be 10 – 30 ms for remote regions connected by long axons (fibres) or 1 – 10 ms for local connections.

Functional Aspects

Alpha Predominance

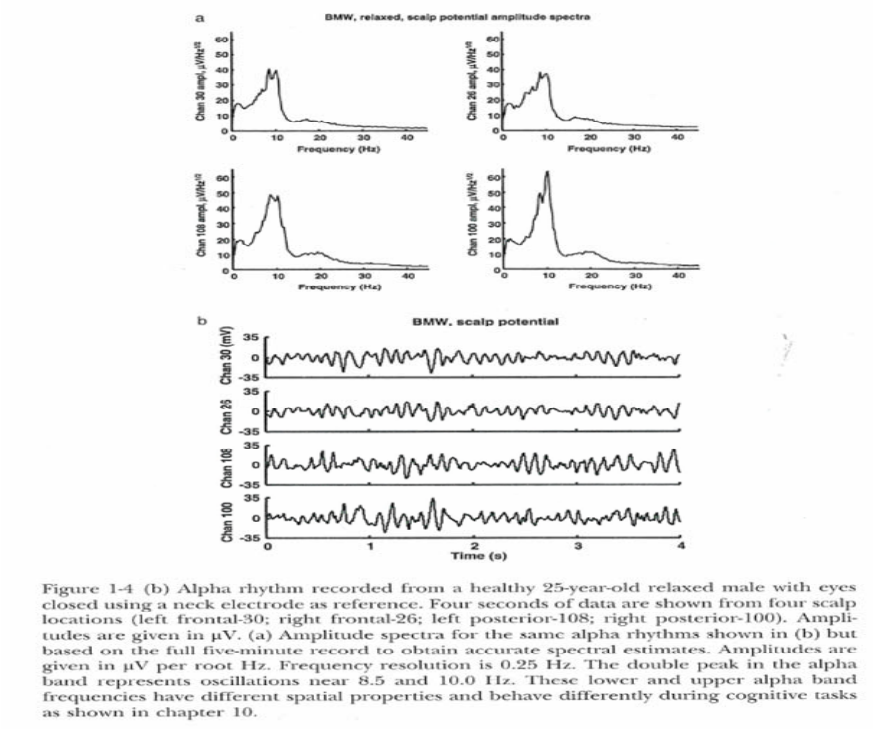


Figure 1-4 (b) Alpha rhythm recorded from a healthy 25-year-old relaxed male with eyes closed using a neck electrode as reference. Four seconds of data are shown from four scalp locations (left frontal-30; right frontal-26; left posterior-108; right posterior-100). Amplitudes are given in μV. (a) Amplitude spectra for the same alpha rhythms shown in (b) but based on the full five-minute record to obtain accurate spectral estimates. Amplitudes are given in μV per root Hz. Frequency resolution is 0.25 Hz. The double peak in the alpha band represents oscillations near 8.5 and 10.0 Hz. These lower and upper alpha band frequencies have different spatial properties and behave differently during cognitive tasks as shown in chapter 10.

From Nunez and Srinivasan 2006

The above figure shows EEG activity recorded from different parts of the scalp. The most recognizable signal observed on the scalp, especially over the occipital (back of head) visual cortex when the eyes are closed in a relaxed subject is the alpha wave [8 – 12 Hz]. Historically this has been the most noticed EEG component. As shown by this figure, it can be recorded at many electrode locations and is the most measured feature in clinical and research studies. The above two figures showing the power spectra of EEG signals also show that even for one subject it is not a single frequency but consists of several alpha frequencies. Further the presence of signals in different bandwidths has been observed for different behaviours and states. Consequently the frequency bands in the figure below are associated with certain states such as level of sleep but the relationship is just correlative and not causal and no neural mechanisms are understood which can explain these different frequency bands.

General Bandwidths

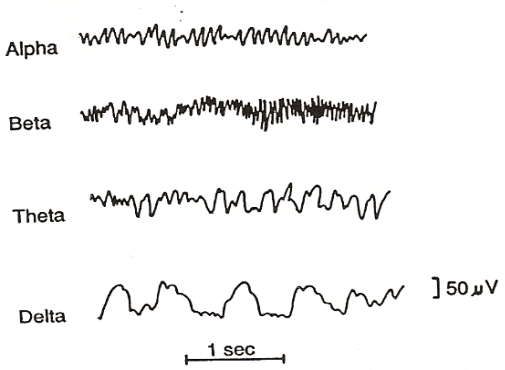


Figure 59–1. Different types of normal electroencephalographic waves.

Table 11-3 EEG Waveform Terminology

Waveform	Frequency (Hz)	Remarks
Alpha rhythm	8–12	Parietal-occipital; associated with the awake and relaxed subject; prominent with eyes closed
Beta rhythm	18–30	More evident in frontal-parietal leads; seen best when alpha is blocked
Delta	1–3.5	Associated with normal sleep and present in children less than 1 year old; also seen in organic brain disease
Theta	4–7	Parietal-temporal; prominent in children 2 to 5 years old

From Webster (1998)

If one records the scalp EEG with a minimum electrode separation of 2.5 cm and good SNR (signal to noise ratio), one can determine the cortical field inside the skull on the dura or cortical surface with a reasonable degree of accuracy using the inverse solution and a knowledge of the geometry and resistive properties of the three dominant tissue layers, CSF (cerebrospinal fluid), bone and scalp. Results have been shown to be independent of the head model used for the volume conduction calculations provided this model contains at least these three layers.

Structural Relationships

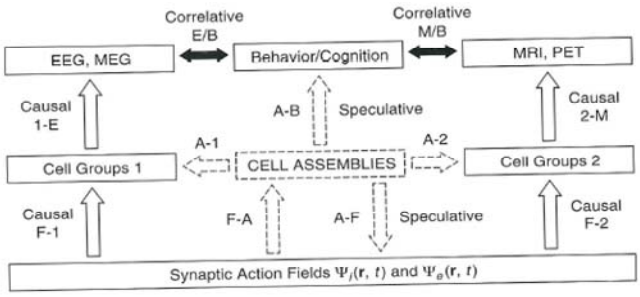


Figure 1-8 A conceptual framework for brain function. Double arrows (near top) indicate established correlative relationships between behavior/cognition and EEG, MEG, MRI, and PET. By definition, cell groups 1 generate EEG or MEG and cell groups 2 generate MRI or PET. Cell groups 1 and 2, which may or may not be part of neural networks (or cell assemblies), are embedded within the larger category (or "culture") of active synapses, the synaptic action fields $\Psi_e(\mathbf{r}, t)$ and $\Psi_i(\mathbf{r}, t)$. These excitatory and inhibitory synaptic action fields may be defined in terms of numbers of active synapses per unit volume or per unit of cortical surface area, independent of their functional significance. Cell assemblies and cell groups 1 and 2 may or may not overlap. Causal and correlative (may or may not be causal) interactions are indicated by hyphens and slashes, respectively. Reproduced with permission from Nunez and Silberstein (2000).

From Nunez and Srinivasan 2006

To help explain the generation of EEG at the scalp from coherent dipole layers of areas of neurons in the cortex, one can think of neurons being organized in dynamic cell assemblies that change to accomplish different functions. These assemblies exist at different spatial scales and can be pictured as embedded within action potential and synaptic activity fields as shown in the above figure. The smallest cell assembly or minicolumn of the human neocortex has .03 mm radius, 3 mm height and contains 100 pyramidal cells with 10^6 synapses. If 10% of theses synapses are active at any time, it is then estimated that to produce a measurable potential (few μvolt) at the scalp, about 6 cm^2 of cortical gyri tissue containing about 60 x 10^6 neurons must be synchronously active and forming a dipole layer.

Cell assemblies can be minicolumns to macrocolumns and are just considered groups of neurons that are working together for the moment. A typical cortico-cortico column could consist of 100 minicolumns. Minicolumns and indeed all neurons in the cortex are highly interconnected with the hypothesized typical path length between any two cortical neurons being only 2 to 3 synapses. In the above figure, the relationships between Synaptic Action fields and Cell Groups 1 is causal and the resulting EEG is causal as well. The idea of cell assemblies is hypothetical and the relationships with the other components in the figure speculative.

Cortical Surface Potential at Location r_1

The time varying cortical surface potential $\Phi(r_1,t)$ at location r_1 is determined by the synaptic activity fields, with the inhibitory field Ψ_i superficial to the excitatory synaptic field Ψ_e as shown in figure 1.9 below. Realistically the excitatory layers in the cortex are mainly I and VI while the inhibitory layers are II through V. The cortical surface potential is then

$\Phi(r_1,t) \approx C_1 \Psi_i(r_1,t) - C_2 \Psi_e(r_1,t)$ where the Ψ_i are current sources and Ψ_e are current sinks

C_1 and C_2 are determined by the distribution of sources and sinks and the volume conduction properties.

The recorded potential has to be a potential difference or voltage since we cannot record potentials relative to infinity. Furthermore all electrophysiological signals are recorded using differential amplification to remove common mode noise thus requiring two inputs. The following figure 1.10 shows this recorded potential V using point electrodes at r_1 and r_2.

$$V(r ,r ,t) = \Phi(r_1,t) - \Phi(r_2,t)$$

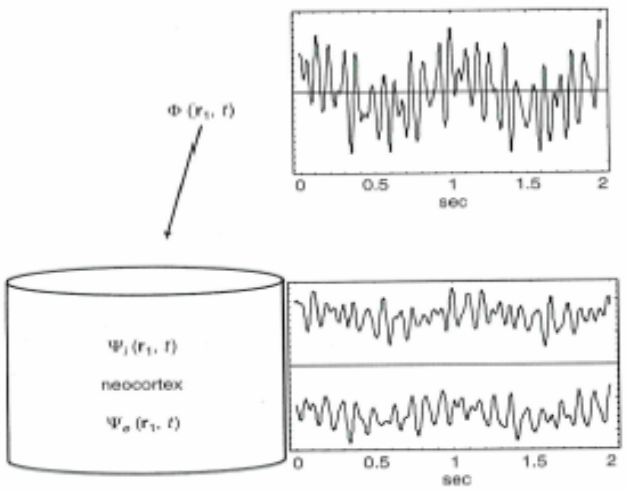


Figure 1-9 Modulations of inhibitory $\Psi_i(\mathbf{r}_1, t)$ and excitatory $\Psi_e(\mathbf{r}_1, t)$ synaptic action densities are imagined here to occur in superficial and deeper cortical layers, respectively. Each waveform shown here consists of five arbitrary frequency components in the delta, alpha, and beta ranges. The simulated cortical surface potential $\Phi(\mathbf{r}_1, t)$ is plotted as a linear combination of these synaptic field variables. A more realistic simulation might have excitatory synaptic action mainly in layers I and VI, and inhibitory synaptic action in layers II through V as indicated in fig. 11-4.

From Nunez and Srinivasan 2006

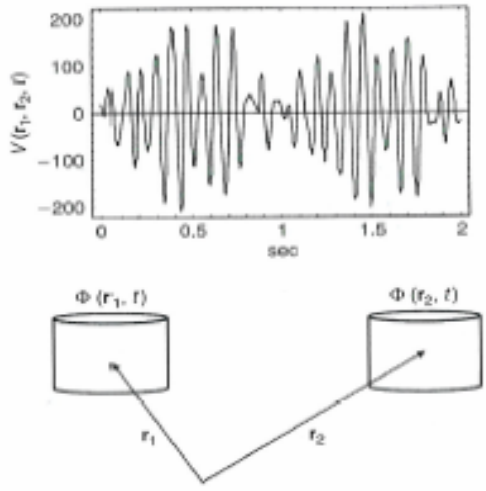


Figure 1-10 In genuine EEG experiments the actual recorded potential $V(\mathbf{r}_1, \mathbf{r}_2, t)$ is the potential difference between two locations $\mathbf{r}_1$ and $\mathbf{r}_2$. In this simulation the 1 Hz delta component included in the simulation shown in fig. 1-9 is common to both locations and does not appear in the recording.

From Nunez and Srinivasan 2006

Basic Assumptions in Production of EEG

- We can consider the distributed current sources to be ideal voltage source as well using Kirchoff's laws
- Current carriers are +ve and –ve ions
- At the frequencies for EP and EEG, capacitive effects of tissue in volume conduction are minimal so volume conductors can be considered as purely resistive networks. This applies to the macro view of tissue since at the micro view such as synapses and excitable membranes capacitances must be considered
- Tissue in the head is inhomogeneous and anisotropic. Hence in modeling field dispersion from a source we use a matrix to represent tissue conductivity.
- At the macroscopic scale tissue can be considered linear and we can apply the principle of superposition.

Recording the EEG

To record either evoked or ambient neural activity we can use an assembly of surface electrodes placed at standardized locations on the scalp known as the 10-20 system as shown in the following figure 4.28. The positions are measured on the scalp relative to the known skull landmarks, from the front at the nasion to the inion at the back of the head and side to side from the two ear canals. This allows researchers and clinicians in different labs to know standardize their measurements and reporting. The electrodes are from 5 to 10 mm diameter and for the macro recording of EEG electrode size in this range is not a factor in determining signal characteristics.
If one wants to record from the cortical surface of the brain, the dura or covering layer, or even within the cortex or deeper structures, a variety of multi-channel electrodes are available such as the shallow "pin cushion" and needle electrodes shown in the next figure. These are fabricated using microelectronic techniques and record from a single to a small number of neurons at each electrode.

Instrumentation (EEG Electrodes)

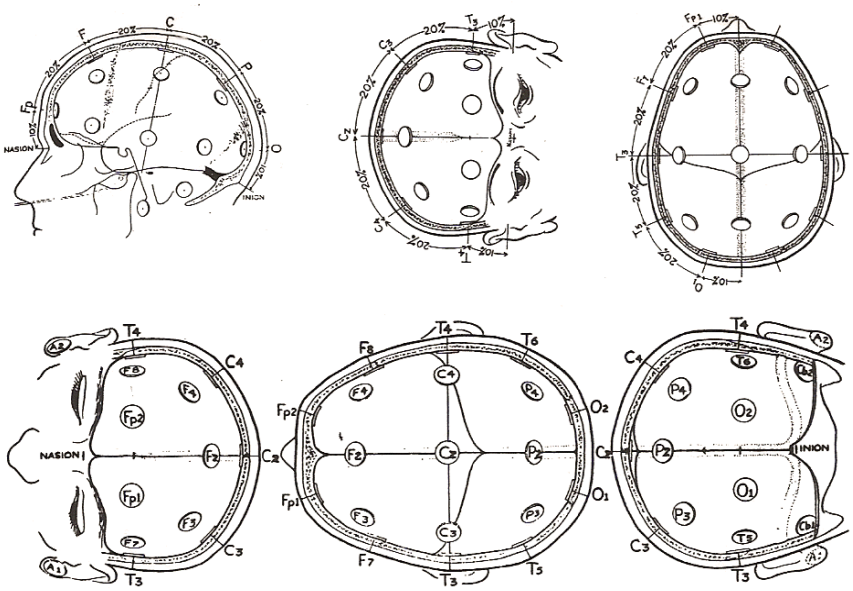


Figure 4.28 The 10-20 electrode system This system is recommended by the International Federation of EEG Societies. (From H. H. Jasper, "The Ten-Twenty Electrode System of the International Federation in Electroencepha-

From Webster (1998)

Cortical Electrodes

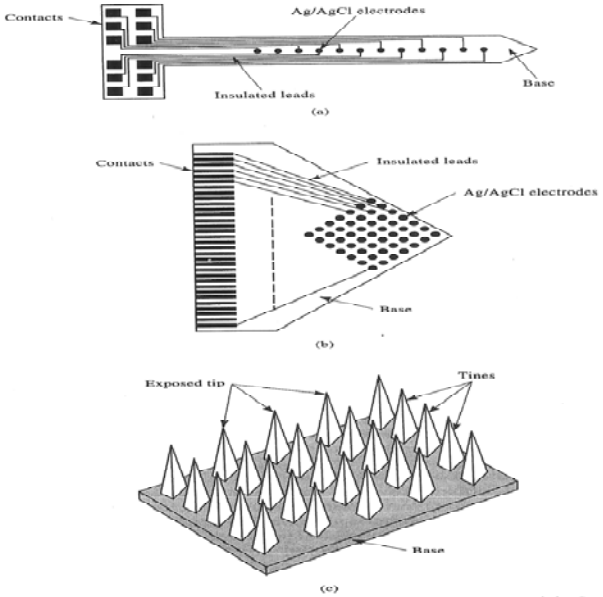


Figure 5.16 Examples of microfabricated electrode arrays. (a) One-dimensional plunge electrode array (after Mastrototaro *et al.*, 1992). (b) Two-dimensional array, and (c) Three-dimensional array (after Campbell *et al.*, 1991).

From Webster (1998)

The surface EEG signals are recorded in a multi-channel fashion using differential preamplifiers and band limiting low pass filters (0.5 Hz to e.g. 50Hz) as shown in the next figure. Since there can be very large common mode 60 Hz signals on the scalp, differential recording techniques are required with a second channel as reference and a third electrode electronically grounded electrode attached at the neck (not shown).

Amplifier Connections

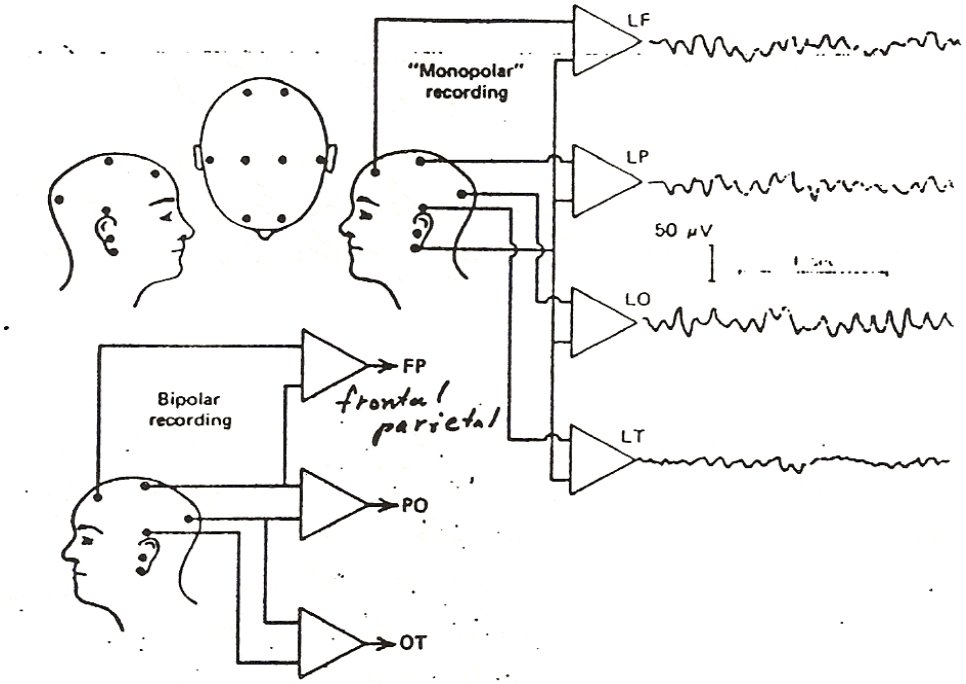


Figure 11-52. Method of connecting the recording channels for "monopolar" and bipolar recording. With "monopolar" recording, the reference electrode is on the earlobe, chin, or neck

Clinical Applications (Spontaneous EEG)

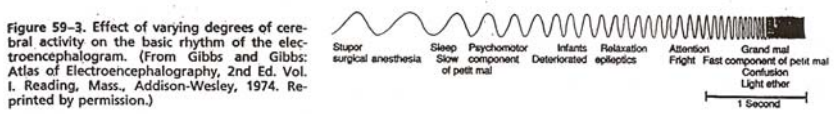
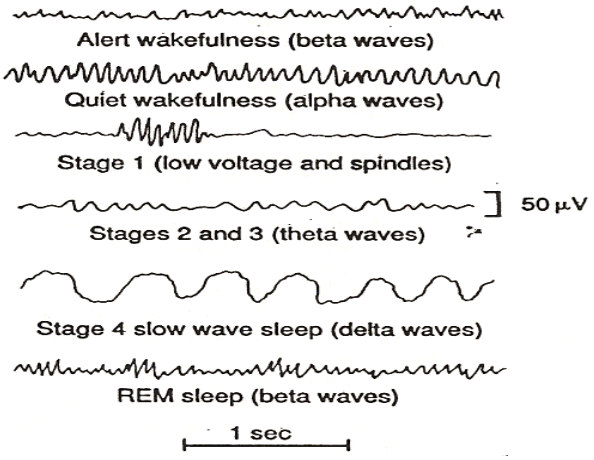


Figure 59–3. Effect of varying degrees of cerebral activity on the basic rhythm of the electroencephalogram. (From Gibbs and Gibbs: Atlas of Electroencephalography, 2nd Ed. Vol. I. Reading, Mass., Addison-Wesley, 1974. Reprinted by permission.)

- Identify presence of lesions (historical)
- Diagnosis and monitoring of epilepsy (seizures)
- Sleep staging
- Estimation of depth of anesthesia
- Other organic brain disease
- Neuropsychiatry (depression, schizophrenia, Altzheimer)

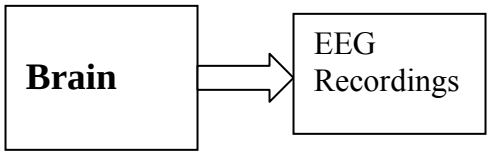
As a first approximation the information in spontaneous EEG is in its frequency content with the very slow components indicating depressed cortical function such as in a stupor or under anesthesia (or deep sleep, following figure) and the faster components indicating intense neural activity such as beta activity or even pathologies such as epileptic seizures. It must be stressed that in clinical applications the bandwidth characteristics and a neural state are associative and little is understood how such clinical states result in the recorded EEG. This question is a very fruitful area of further research, and new single and multi-channel signal processing and pattern recognition strategies should shed some light.

Sleep Staging

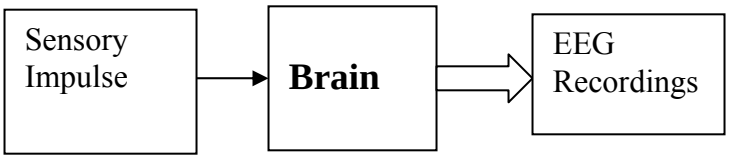


Brain Evoked Potentials

These are special uses of the EEG signal and are not limited to the bandwidth of normal EEG (1 Hz – e.g. 60 Hz) recorded while the subject sits still. In engineering terms EEG is just monitoring a multi-output system with no controlled inputs.

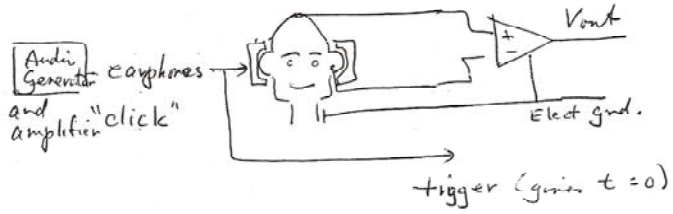


Evoked potentials use the more common approach where you determine the transfer function (characteristics) of a system by driving it with a known input (physiological impulse) and measuring the output. We can use the sensory inputs to the brain to stimulate it with one input, hopefully keeping the other inputs constant or 0.



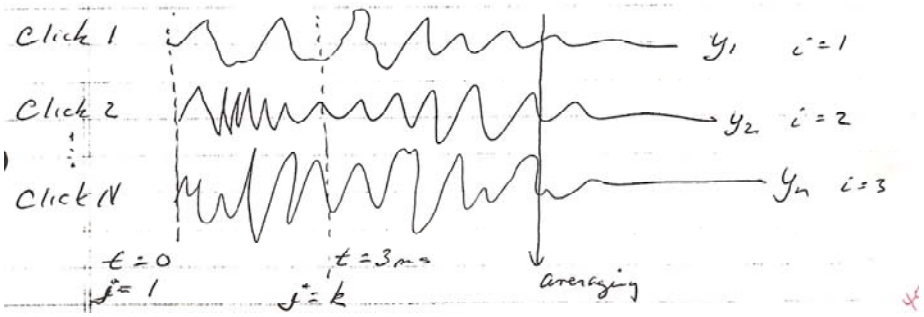
Brain Stem Auditory Evoked Potential (BSAEP)

This evoked potential (EP), is the output of the auditory pathways of the brainstem to supra threshold "clicks" presented to the ear of the subject. It is a subset of the entire brain auditory response and occurs within approximately the first 10 msec. Because of this very short latency, it is not confounded by any auditory cognitive processing and is therefore considered a true EP and assumed to be deterministic, changing neither in shape or time of occurrence relative to the time of the stimulus.



Clicks are sent to the ear at an amplitude above threshold where increases in the click amplitude do not affect the BSAEP amplitude or shape. They are delivered at a rate of 10 Hz. For each click the auditory signal is conducted along the cochlear (auditory) nerve to the brainstem which lies deep in the skull under the cerebrum. It is then sent on to the via additional synapses and pathways to the auditory cortex in the superior gyrus (fold) of the temporal lobe. The BSAEP is used to determine the health of the brainstem in those patients with neurological disease or suffering from neural trauma such as a stroke or head injury. It is also used to determine if the hearing apparatus, including the cochlea is

healthy, and since the test requires no cognitive response from the subject can be performed on very young children in the first months of life to determine deafness. This is very important since the best results when implanting hearing technology such as the artificial cochlea are achieved when the implant is done at a very ealy age when the auditory cortex is still developing in the child. V_{out} in the above figure is a sum of the BSAEP, physiological noise such as cortical EEG, and environmental and instrumentation noise. The BSAEP has a bandwidth of 150 Hz to 2500 Hz (well above the bandwidth of ambient EEG but is in the amplitude range of hundreds of nanovolts, which is well below the input instrumentation noise of all amplifiers. Even by filtering out most ambient cortical EEG and any remaining environmental noise (almost all 60 Hz is removed by the differential amplifier by its common mode rejection) using a bandpass filter from 100 Hz to 3 KHz, we are still left with the broadband instrumentation noise in the μvolt range. Therefore the signal to noise ration in db is negative. There are no sophisticated signal processing techniques available to reliably extract the BSAEP from the much larger noise signal. The current commercial technique is ensemble or synchronous averaging. This requires that the clicks are repeated over time (BSAEP clicks at 10 Hz) and the response recorded for each click as shown below.



Each click i , i = 1 – N, results in the recorded signal y_i which contains both the BSAEP and noise. Time 0 is the time of the click or impulse. Averaging requires that the signal be sampled over time, using a sample rate of 50 KHz resulting in approximately 500 samples for the 10 msec of recording. The sample index j then goes from 1 at time 0 to 500.

The output for click i can be represented by

$$y_i = s_i + n_i$$

where s_i is the BSAEP and n_i is the additive noise. In the sampled data response we can write

$$y_{i,j} = s_{i,j} + n_{i,j}$$

where $y_{i,j}$ is the jth sample for the ith response.

If we ensemble average the N responses we get

$$1/N\sum_{i=1}^{N} y_{i,j} = 1/N\sum_{i=1}^{N} s_{i,j} + 1/N\sum_{i=1}^{N} n_{i,j\,j} \qquad \text{eqn 1}$$

If we make the following assumptions:

- the BSAEP is deterministic and invariant for any i ($s_{i,j}$ is constant for each j)
- the noise is random for each j and uncorrelated from stimulus to stimulus
- the noise has zero mean (usually valid for instrumentation noise since the signal is high pass filtered

Then the $n_{i,j\,j}$ term in equation 1 goes to 0 if N is large enough and the $s_{i,j}$ terms becomes simply s_j . The ensemble average of the recorded output then is only the BSAEP. Notice, no assumptions have been made about the noise characteristics or statistical properties other than it is random and uncorrelated. We do not know whether the BSAEP is constant from stimulus to stimulus since single BSAEP have not been measured except in rare occurrences. Studies using sequential ensembles of 100 have shown that there can be small variances in the average BSAEP but these changes are not consistent with time. The assumption of a deterministic BSAEP is consequently still generally accepted. In general, instrumentation noise and the background high frequency EEG have zero mean, and are random and uncorrelated so most of our assumptions are valid. However, in other applications of ensemble averaging of electrophysiological signals, the stimuli can be delivered by electrical or magnetic pulses and $n_{i,j}$ then may include the stimulus artefact which is not random and is correlated to the desired EP. Ensemble averging will not remove the stimulus artefact and indeed has no effect on it. Other means have to be found to remove this artefact.
Although the averaging technique is very robust because it makes few assumptions, it is also quite inefficient requiring a great many stimuli if the SNR is very poor. In the case of the BSAEP, N is usually 2048 requiring more than 200 seconds of 10 Hz clicks. If the noise is assumed to be Gaussian zero mean, the SNR improves with $\sqrt{N}$. For non Gaussian noise such as large muscle or other artefacts, the performance is seriously degraded. However, large artefacts can be detected by an amplitude discriminator and that particular y_i then discarded prior to including it in the average.
The complete auditory response is shown on the following figure, with the BSAEP in the first 10 msec, and the more cognitively affected event related potentials (ERP) shown in the 100's of msec range.

Evoked responses associated with the other sensory systems, such as visual and somatosensory can also be derived using ensemble averaging with N determined by the SNR. Other EPs or ERPs can be obtained by directly stimulating regions of the brain using magnetic stimulation and this field is just beginning.

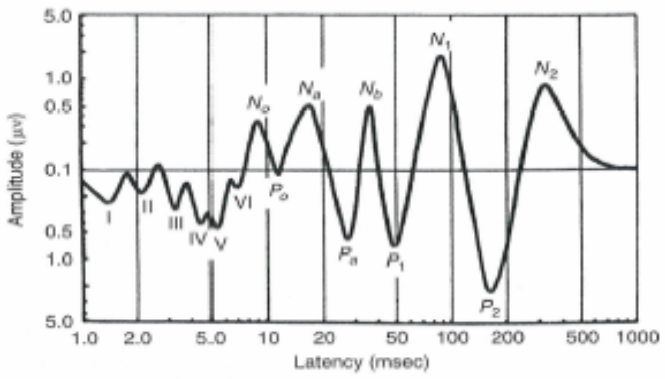


Figure 1-17 The auditory evoked potential waveform as recorded from the human scalp. A subject is presented with a series of up to several thousand tones or clicks and the time-locked EEG is averaged over the stimuli to remove the (much larger) spontaneous EEG. The first few ms of the waveform is also known as the brainstem averaged evoked response (BAER). Physiologists have assigned standard labels to each peak (N_1, P_2, and so forth). Reproduced with permission from Picton et al. (1974).