EE 791
EEG Lecture 3

Fallacies in EEG

EEG is not an epiphenomenon

Ever since its first identification in the 1920's, EEG has ridden a roller coaster of acceptance. At first it was seen as a picture on the brain describing and identifying brain function. During the decades following it has lost much of its lustre, especially when CAT and MRI scans allowed us to see brain structure in general and even very small lesions in particular. With the advent of PET, SPECT and fMRI, we now can also visualize brain function. EEG has been relegated to serve in a few very specific areas, e.g. sleep staging, assessment and treatment of epilepsy. Is the EEG an epiphenomenon (a measure peripheral to genuine scientific interest)? Given the much greater interest in EEG during the last two decades, where many researchers are now trying to use EEG to predict the onset of a seizure and even in several studies providing contraceptive intra-cranial "defibrillation", predicting treatment in neuropsychiatric diseases and becoming a reliable control source for environmental response and manipulation, this statement is false. As well evoked and event-related potentials have shown their utility now that ensemble or synchronous averaging or even more complex processing is possible with even the simplest processor. Of course, the new interest in, and utility of EEG is a result of advances in microelectronics and microcontroller and processor computational speed. However, many controversies still exist. One of the problems is matching the temporal-spatial scale of the recorded EEG with the temporal-spatial scale of the physiological event. Where EEG has very good temporal resolution, spatial resolution remains a problem. For example intracranial electro-cortical are dependent on electrode size where scalp recordings (within reason) are not. Further it is difficult to match the former to the much larger spatial latter. The former can record from a number of coherent and incoherent sources while the latter can only record from coherent sources because of the much larger distance and signal attenuation. There is also considerable chauvinism based on scale of recording where each researcher feels his/her scale is most important, i.e. electrophysiologists prefer intracranial recordings with very small electrodes, where psychologists and clinicians like the larger scale scalp potentials which are readily accessible and hopefully describe the function of larger brain structures.

EEG practice divorced from theory

There exist a variety of models and expertises in the engineering world. Think of the progressive scales in electronics, starting with the non-linear junction behaviour in semiconductor physics, or even quantum events at the atomic level, to the structure of the transistor, to the structure of the integrated circuit, to applied linear circuit theory, to large scale circuits. The same is true of electrophysiology starting with the cell membrane, linear and nonlinear Hodgkin-Huxley behaviour to produce propagating action potentials, extra-cellular field recordings of a few neurons to populations of neurons, and distance recordings of millions of neurons as measured by their synaptic fields (EEG). Two general approaches are used in modelling EEG: volume conductor models of electric potentials recorded at a distance from the generating sources and very much determined by the volume conductor properties and distance; and models of the dynamic behaviour of brain current sources. In volume conduction the medium may be anisotropic and inhomogeneous but it remains linear so the principle of superposition applies at

least in a macroscopic scale. As well, at the frequencies encountered in electrophysiological signals the volume can be considered purely resistive with no time or phase delays due to conduction. This considerably simplifies interpretation of results. Unfortunately the more microscopic current source models, while attractive theoretically do not lend themselves to experimental verification, clinical utility or interpretation on even a modest macro scale. Neural networks, while very useful in the machine learning world of biomedical engineering, are neither physiologically/anatomically based models of behaviour nor describe volume conduction of macroscopic potential fields.
Generally, the potential difference between any two scalp locations depends on all sources plus the volume conduction properties of the head. The statement that EEG is only the result of signals from the neocortex, does not apply in general and large coherent sources deeper in the brain can also contribute to the EEG, not to mention evoked potentials from small nuclei in the brain stem. It all depends on the paradigm used for obtaining the scalp signal and the signal processing required.

Representation of a source by a dipole
If the recording site is at least 3 to 4 times the diameter of the source away from that source it can be modelled as a dipole. Therefore the field drops off at $1/r^2$ if tissue inhomogeneity and anisotropy are ignored. However, much EEG at scalp is 1/5 to 1/2 the magnitude of cortical EEG despite a distance of 1 cm (i.e. instead of 100 μV cortical dipole being 1 μV at scalp surface it is 50 μV). This can be explained by there being a dipole layer from many synchronously active parallel neurons, shown in Fig 2-3 – a dipole sheet with much less attenuation at distance (i.e. the spread of current to adjacent tissue is much less).

Example 1
If a dipole is in a tank of "infinite dimensions" Φ(r,θ) in the tank at location r,θ, where r is the distance to the position from centre of dipole and θ is the angle between dipole and direction r.

$$\Phi(r,\theta) \cong \frac{I d \cos\theta}{4\pi \sigma r^2} \qquad r \gg d$$

d is distance between poles of dipole, σ is conductivity of fluid, I is dipole strength.

$$\therefore \Phi(r_1, r_2) = \frac{1}{4\pi\sigma}\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$

If $I = 10\,\mu A$, $d = 1\,mm$, $\sigma^{-1} = 350\,\Omega\cdot cm$.

$$I(r,0) \simeq 464\,\mu V \qquad r = 2.5\,mm.$$
$$\simeq 12\,\mu V \qquad r = 1.5\,cm. \text{ ideally}$$

If non-ideal effects such as skull σ, etc. are included then reduce this by a factor of 4

Cortical potential/Scalp potential ≈ 100-200 as shown in following figure

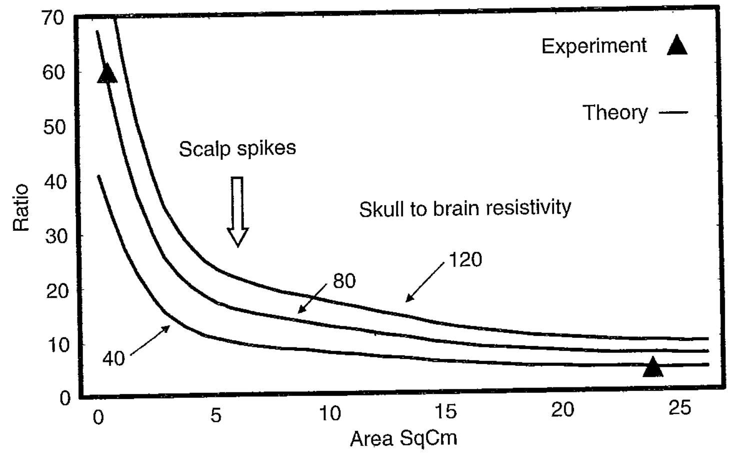

Figure 1-20 Theoretical estimates of the ratio of dura potential to scalp potential expressed as a function of "synchronous area" of active cortical sources. The three curves were generated by assuming cortical dipole layers of constant (mesoscopic) sources in the 3-sphere head model. The assumed skull to brain (or scalp) resistivity ratios are shown (40, 80, 120). The two triangles are the only available experimental points known to us (Abraham and Ajmone-Marsan 1958; Goldensohn 1979). The large arrow near the steep upturn in the curves indicates the clinical observation that epileptic spikes must be "synchronous" over at least 6 cm^2 of cortex in order be recognized on the scalp (Cooper et al. 1965; Ebersole 1997). Reproduced with permission from Nunez et al. (2001).

Neurologists generally rule that a cortical dipole layer of synchronously active neurons must be at least 6 cm^2 for epileptic spike detection. If the area becomes 10 – 20 cm, ratio can be ≈ 2 – 5.

Experimental observations support this:

- RMS of spontaneous cortical EEG is 2 – 5 times simultaneously recorded scalp potentials
- At least 6 cm^2 of cortex must be synchronously active to record without averaging. If not 40 μV of alpha at scalp would imply mV at cortex for a single dipole
- Alpha and sleep rhythms recorded from several cm deep in brain have similar magnitudes to cortical surface potentials.
- EEG frequency spectra recorded at scalp and cortex are similar in range 0 – 15 Hz. Much more beta (15 – 30 Hz0 recorded at cortex surface than scalp.

Example 2 The Forward Problem

In the forward problem, the sources and their locations in the brain (dipoles) are known and with certain assumptions about the electrical properties of the brain, the scalp potentials can be calculated with a unique solution. The boundary conditions that no current flux exits the head even at the neck is a reasonable assumption. The microscopic source function s(r,t) is too far removed from the scale of scalp recordings so the mesosource function (dipole moment per unit volume, P(r,t)) is used instead. The forward problem can be used to address common EEG problems and guide in interpreting EEG. Figure 2-1 shows an example of this where a distribution of 4200 MM scale cortical dipoles is assumed along with a 3 sphere head model to predict scalp potentials. In this figure no dipoles are placed within 5 cm of right ear so it can be used as reference. One +ve and two –ve cm scale areas are consistently placed for the two cases.

Cortical Contributions

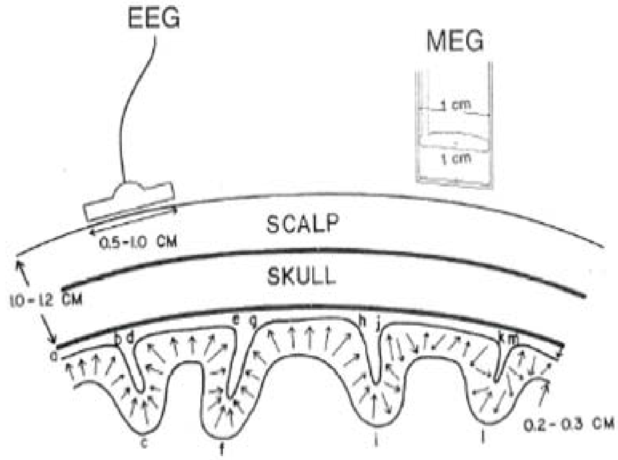

Figure 2-3 Neocortical sources can be generally pictured as *dipole layers* (or "dipole sheets," in and out of cortical fissures and sulci) with mesosource strength varying as a function of cortical location. EEG is most sensitive to correlated dipole layer in gyri (regions ab, de, gh), less sensitive 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).

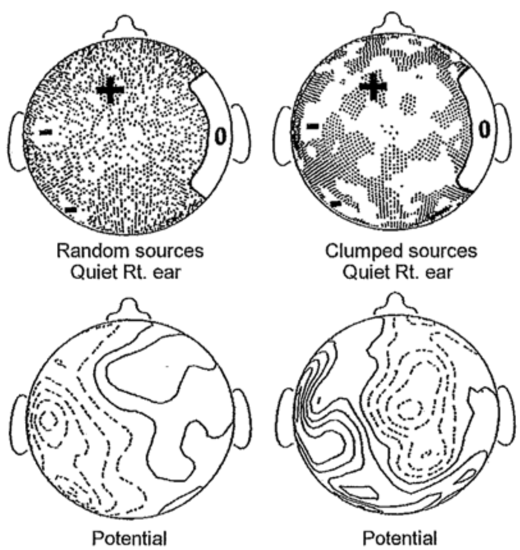

Figure 2-1 A simulation using 4200 radial dipoles (macrocolumn-scale mesosources) in a 3-sphere model of the head (brain, skull, and scalp). (*Upper row*) Filled and empty spaces indicate positive and negative source regions, respectively, with random magnitudes. The region near the right ear labeled "0" has no sources. The three clumped regions indicated by the ± signs remain unchanged as the background source pattern changes from random (upper left) to clumped (upper right). (*Lower row*) Calculated scalp potential maps predicted for a reference electrode on the right ear or mastoid. Reproduced with permission from Nunez and Westdorp (1994).

Example 3 The Inverse Problem
If one records from 20 – 128 locations, assumes N dipole sources each with 6 parameters: 3 spatial coordinates, two dipole axis angles and the dipole moment (μamp mm), one can obtain some optimum fit of the 6N parameters to the surface recorded signals (a window or time slice). However there is no unique solution, unlike the forward problem. Figure 2-2 shows a single dipole source. To determine the number of dipoles N and their locations requires a priori assumptions which may not be realistic.

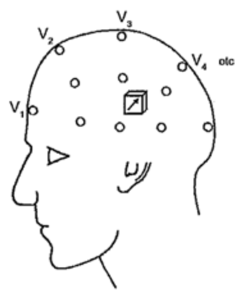

Figure 2-2 Dipole searches employing sophisticated computer algorithms are based on potentials recorded at perhaps 20 to 128 surface locations, either for fixed time slices or over some time window. If *N* dipoles are assumed, the algorithms attempt to calculate the 6*N* parameters that best fit the recorded data—three location coordinates, two axis angles, and one strength (dipole moment) for each dipole. Application of additional *constraints* (often assumptions) may be used to reduce the number of parameters to be found.

In general the inverse solutions computed source locations are no better than the model assumptions. Cortical dipole layers are believed to produce nearly all spontaneous scalp EEG of moderate to large amplitude. Therefore the inverse problem is more tractable if we assume just cortical layer sources.
One cannot use simple volume conduction models with simple sources as used for action potential recording from muscle fibres or neurons, but must use large dynamic models. This will involve simplifying assumptions but it is the only way to design experiments and understand the results.

Misuse of Physical and Mathematical Models
Physical Models

- Phantom heads with implanted current sources
- Can be used to test new software algorithms and hardware to improve spatial resolution, locate sources, map amplitude distributions and create virtual populations by employing dynamic or variable sources
- They are well trusted by medical scientists because they can be visualized

Mathematical Models

- Not trusted as readily (with some justification)
- Physical principles must be used to develop mathematical models although these are of necessity highly simplified.
- Mathematical models are used to create physical prototypes for laboratory testing
- Mathematical models, when successful are a necessary but insufficient condition for successful prototyping.

Errors in Developing Mathematical or Physical Models of Brain Dynamics

- Attributing strange non-ohmic electrical properties to living tissue (1.e. capacitive properties at physiological frequencies). Macro passive tissue is **not** a low pass filter.
- No magnetic induction effects in tissue at frequencies below 10^6 Hz. There is no electromagnetic propagation or far field associated with any measurable EEG phenomenon.
- Confusion between charge sources that produce potentials in dielectrics (piezoelectric)and current sources that produce potentials in conductors
- Correcting volume conduction distortion of EEG using tissue boundary information from CT or MRI. You need both geometry and electrical properties.
- Placing all mathematical models in the same category. For example head models based on a homogeneous sphere or two spherical shells have minimal use in EEG. Three to four shell models including critical skull and scalp current paths appear to provide good semi-quantitative predictions of EEG observations.
- Confusing metaphor with genuine theory. Metaphor may help theory explanations but we should reserve theory to models that contain only physiological parameters, with at least one predicted parameter being measurable. A culprit here is Neural Network Models which are not based on physiological parameters. Models that predict brain "activity" should be suspect if that activity is not defined as physiological (e.g. synaptic fields or action potentials).
- Inappropriate crossing of spatial scales or hierarchical levels. For some published theories: (a) the mathematics is supposed to apply to all spatial and temporal scales; (b) the scale that fits the theory can be magically found; (c) the authors are unaware of the importance of spatial or temporal scales in connecting genuine theory to experiments. For instance what size of measuring electrode would be required? A less serious error is to apply a successful theory from one scale to a different scale without justification.
- Limitations placed on spectral (Fourier) analysis to requiring the system to be linear. A mathematical function (signal) in the interval [0,T] has a Fourier transform if:
    1. it is piecewise continuous (discontinuities must be finite in number)
    2. mean square integral of [0,T] must exist (amplitude bounded)
    3. has a finite number of maxima and minima in [0,T]
    4. periodic (with T)

The Quiet Reference Myth

- Reference should have no electrical source near it
- We don't know the location of brain sources and thus can't assume the reference is far away from it
- Sources in the brain are widely distributed
- A number of coherent sources far away from the reference will add and contribute to the reference potential
- Arbitrary reference locations can lead to erroneous results and conclusions
- Linked ear references may result in distorting the electrical fields of each hemisphere. Although that is the conclusion by the textbook's authors I don't believe this and it would be true if the reference electrode impedances were near 0.

Artifact Free Data

- When reading papers be wary of the phrase "artefact free data" was analysed
- Some obvious artifacts such as eye-blinks or excessive eye-movement are usually recognized and the data segment rejected.
- 60 Hz power line interference usually because of high electrode impedances and a poor electromagnetic environment are recognizable and the dat rejected.
- High electrode impedances can also result in baseline movement from motion artefact induced by the electrode leads. This "swinging lead" phenomenon can be interpreted as delta or even theta activity. Large movement artefact will saturate amplifiers and is easily recognized
- In recent years the EEG bandwidth has been increased to well above 30 Hz and now includes beta-1, beta-2, gamma-1, gamma-2, existing all the way up to 60 Hz and beyond. Beta and gamma differences between populations could easily be due to muscle activity in temporalis, occipitofrontalis or other scalp muscles since EMG bandwidth is from 20 – 250 Hz with higher amplitudes in the 40 -100 Hz range. Some authors have reported higher gamma levels in the anxious subject population but even light tooth pressure or jaw clenching will produce large EMG signals in temporal, frontal, central and parietal electrodes.
- ECG artefact can be present in lower scalp electrodes such as F7, F8, T3, T4, T5, T6 and although of low amplitude compared to EMG can still increase power in the beta and gamma bands.

New Data Analysis Methods in Search of an Application

There is an understandable suspicion by clinicians and cognitive scientists of computer processing techniques.

- Clinicians are very competent at visually interpreting EEG. Computer methods should complement not replace human talents
- However, multi-channel data are too complex temporally and spatially for ready visual analysis
- Is it necessary to go beyond the 10-20 system? What do additional channels give you?
- Inappropriate computer methods are worse than no computer methods at all. Computer algorithms give numerical and sometimes graphical results which take on a life of their own and are sometimes accepted at face value.
- To be proposed as useful, new techniques should be tested using physical models if possible and in any case there should be some method of validity testing.
- No matter how sophisticated the computer method, raw data should never be ignored. Remove the "black box" idea of mathematics. Results of analysis using computer programs (and complex mathematical algorithms) should be consistent with scientific intuition (even post hoc intuition).
- **USE COMMON SENSE**