Analysis of Brain Electrical Activity and applications

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Nancy, 2014
Contents

- What is EEG
- EEG methodology
- EEG spectral analysis
- EEG in epilepsy
- Epileptiform patterns localization
- Epileptic seizures prediction
- Brain-Computer Interface
The Nervous System

Central Nervous System

Brain (Cerebrum)
- Frontal Lobe (Consciousness)
- Parietal Lobe (Movement and stimulus perception)
- Temporal Lobe (Speech recognition)
- Occipital Lobe (Vision)
- Midbrain
- Brain Stem (Basic, vital functions and breathing)

Spinal Chord

Peripheral Nervous System

Autonomic (Somatic, control systems)
- Lymphocytes
- Monocytes
- Macrophages
- Blood vessels
- Bone marrow
- Thymus
- Lungs
- Liver
- Intestines
- Pleur plaques

Somatic (Voluntary, muscle movement)
- Parasympathetic (Rest and Digest)
- Sympathetic (Fight or Flight)
EEG history-1

1875 Richard Caton records brain potentials from cortex of dogs and apes

In 1924, Hans Berger

- Recorded brain activity from the closed skull
- Reported brain activity changes according to the functional state of the brain (1929)
  - Sleep
  - Hypnosis
  - Pathological states (epilepsy)
  - Cerebral injury
Über das Elektrenkephalogramm des Menschen.

Von

Professor Dr. Hans Berger, Jena.

(Mit 17 Textabbildungen.)

(Eingegangen am 22. April 1929.)

Wie Garten 1, wohl einer der besten Kenner der Elektrophysiologie, mit Recht hervorgehoben hat, wird man kaum fehlgehen, wenn man jeder lebenden Zelle tierischer und pflanzlicher Natur die Fähigkeit zuschreibt, elektrische Ströme hervorzubringen. Man bezeichnet solche Ströme als bioelektrische Ströme, weil sie die normalen Lebenserscheinungen der Zelle begleiten. Sie sind wohl zu unterscheiden von den durch Verletzungen künstlich hervorgerufenen Strömen, die man als Demarkations-, Alterations- oder Längsquerschnittsströme bezeichnet hat. Es war von vornherein zu erwarten, daß auch im Zentralnervensystem, das doch eine gewaltige Zellanhäufung darstellt, bioelektrische Erscheinungen nachweisbar seien, und in der Tat ist dieser Nachweis schon verhältnismäßig früh erbracht worden.

Caton 2 hat bereits 1874 Versuche an Kaninchen- und Affenhirnen veröffentlicht, bei denen unpolarisierbare Elektroden entweder an der Oberfläche beider Hemisphären oder die eine Elektrode an der Hirnrinde, die andere an der Schädeloberfläche angelegt worden waren. Die Ströme wurden zu einem empfindlichen Galvanometer abgeleitet. Es fanden sich deutliche Stromschwankungen, die namentlich beim Erwachen aus dem Schlaf und beim Eintritt des Todes sich verstärkten,
EEG definition

An **electroencephalogram** (EEG) is a record of multichannel signal of potential differences, that can be registered on the intact head surface.

- EEG is the only measurement modality describing the **functioning** of the brain, since all processes in the brain related to the information processing are of electrical nature.
Four applications of EEG

• Evaluation of brain disorder in clinic
• Studying brain functioning in the lab
• Therapeutic application as biofeedback
• Deciphering thoughts and intentions in BCI
EEG of healthy subject
1) When an Action Potential reaches the axon terminal the neuron releases a neurotransmitter.

2) The postsynaptic neuron gets depolarized or hyperpolarized, resulting in Excitatory or Inhibitory Post-Synaptic Potentials. EPSP and IPSP summate temporally and spatially.

3) When an EPSP is generated in the dendrites of a neuron an extracellular electrode detects a negative voltage difference, resulting from Na\(^+\) currents flowing inside the neuron’s cytoplasm.

4) The current completes a loop further away the excitatory input (Na\(^+\) flows outside the cell), being recorded as a positive voltage difference by an extracellular electrode.

This process can last hundreds of milliseconds.
Origin of EEG signal - 2
**Electrodes location – 10/20 system**

**Nasion:** point between the forehead and the skull

**Inion:** bump at the back of the skull

**Location:** Frontal, Temporal, Parietal, Occipital, Central

**z** for the central line

**Numbers:** Even numbers (2,4,6) - right hemisphere, odd (1,3,5) – left hemisphere
**EEG recording**

Channel: Recording from a pair of electrodes (here with a common reference: A1 – left ear)

**Multichannel EEG recording:** up to 256 channels recorded in parallel

**Reference electrode:** Mastoid, nose, ear lobe…
EEG reference systems
EEG electrode placement
EEG recording
OpenEEG project

Diagram showing circuit components and connections for the OpenEEG project.
EEG of healthy subject
EEG during epileptic seizure
EEG rhythms – 1

Beta (β) 13-30 Hz
Parietally and frontally

Alpha (α) 8-13 Hz
Occipitally

Theta (Θ) 4-8 Hz
Children, sleeping adults

Delta (δ) 0.5-4 Hz
Infants, sleeping adults

Spikes

Epilepsy - petit mal

V [µV]

Time [s]
<table>
<thead>
<tr>
<th>Rhythm</th>
<th>Frequency (Hz)</th>
<th>Amplitude (uV)</th>
<th>Location</th>
<th>State of mind, Source of activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha (α)</td>
<td>8 – 13</td>
<td>50 – 100</td>
<td>Occipital, Parietal regions</td>
<td>Adults, <strong>rest, eyes closed</strong>. Alpha blockade occurs when new stimulus is processed. Oscillating thalamic pacemaker neurons.</td>
</tr>
<tr>
<td>Beta (β)</td>
<td>14 - 40</td>
<td>2 – 20</td>
<td>Frontal region</td>
<td>Adult, <strong>mental activity</strong>. Reflects specific information processing between cortex and thalamus</td>
</tr>
<tr>
<td>Gamma (γ)</td>
<td>40-70 (100)</td>
<td>5 – 7</td>
<td>Variable location</td>
<td>Is believed to be reflecting mental activity, consciousness, meditation states etc. Associated with <strong>sensory processing</strong>.</td>
</tr>
<tr>
<td>Delta (δ)</td>
<td>0.5 – 4</td>
<td>Above 50</td>
<td>Variable location</td>
<td><strong>Deep sleep</strong>, children in sleep. Oscillations in Thalamus and deep cortical layers. Usually inhibited by ARAS (Ascending Reticular Activation System)</td>
</tr>
<tr>
<td>Theta (θ)</td>
<td>5 – 7</td>
<td>5 – 100</td>
<td>Occipital</td>
<td>Children, <strong>drowsy adult, sleepiness</strong>, emotional distress. Nucleus reticularis slows oscillating thalamic neurons, therefore sensory throughput to cortex diminished.</td>
</tr>
<tr>
<td>Mu (μ)</td>
<td>8 – 13</td>
<td>up to 50</td>
<td>Motor cortex</td>
<td>Associated with <strong>sensorimotor</strong> transformation. Suppressed when person performs real or imaginary motor action.</td>
</tr>
</tbody>
</table>
EEG spectral analysis

- In classical Fourier analysis the signal is represented as a sum of sinusoidal oscillations of harmonically increasing frequencies

\[ F(j\omega) = \int_{-\infty}^{+\infty} x(t) e^{-j\omega t} dt \]

\[ c[m] = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x[n] e^{-2\pi j \frac{m}{N} n} \]
Quantitative EEG (qEEG)

Topographical maps plot EEG data on a map of the brain surface.

Usual data plotted:

- ERP maps
  - potential changes
- Spectral maps
  - frequency changes
- Statistical maps
  - comparison of measurements
Brain functional regions
Time-frequency analysis

- TFA allows to track time changes in spectral contents of EEG signals
- Short-Time Fourier transform is used to analyze EEG

\[ F_w(\omega, \tau) = \int_{-\infty}^{\infty} x(t)w(t-\tau)e^{-j\omega t}dt \]

\[ c[m,k] = \sum_{n=0}^{N-1} x[n]w[n-k]e^{-2\pi j \frac{m}{N}n} \]
Real-time Brain activity mapping
Epilepsy

- **Epilepsy** is a group of diseases characterised in most cases by repeated sudden unpredictable seizures caused by excessive abnormal synchronous activity of neuronal groups in the brain.

- Clinical manifestations of epilepsy are unforeseen and abrupt motor phenomena like tremor and convulsions, lost of consciousness, breathing pauses and respiratory changes, hallucinations, screaming and other psychic and sensory symptoms.

  - **Causes:** insults, trauma, vascular diseases, infections, neurodegeneration, inflammations, cysts, tumors, genetic inclinations, developmental defects.
Epileptic seizures

- **Partial (focal)**
  - Simple partial
    - Motor
    - Somatosensory
    - Autonomic
    - Psychological
  - Complex partial
    - Simple partial with impaired consciousness
  - Partial seizures with secondary generalization

- **Generalized**
  - Absence
  - Tonic
  - Clonic
  - Tonic-clonic
  - Atonic
  - Myoclonic
EEG activity in Epilepsy

- Epilepsy
  - Normal activity
  - Abnormal activity
    - Inter-ictal
    - Ictal
      - Pre-ictal
        - Focal activity
        - Multifocal
      - Generalized activity

Targets of EEG analysis in epilepsy

Automated analysis of EEG

Epileptic activity detection

Epileptic spike detection

Epileptic seizure analysis

Seizure detection

Seizure prediction

Seizure classification

Seizure focus localization
Epileptic seizure analysis

Features of seizure activity
- Spectral and wavelet characteristics
- Amplitude distribution
- Spatial distribution
- Chaotic characteristics

Classification of seizure activity
- Nearest neighbor
- Artificial Neural Nets
- Support Vector Machines
- Decision Trees
- Fuzzy Classifiers
Epileptic Pattern Localization

- Epileptic oscillation complexes in human electroencephalogram - complexes of a sharp wave and a slow wave, indicating the presence of neuronal epileptic discharges in the brain.
Epileptiform Complexes – 1

- At the **early stages of disease**, epileptiform complexes are rare, distorted, non-prominent and low-amplitude.

**Objective** – to detect and properly localize the epileptiform complexes in EEG.

**Early detection** –
  - earlier start of **treatment** –
  - more favorable prognosis of **recovery**
Template for the Class of Epileptiform Complexes

«generic» epileptiform complex

Parameters of possible acceptable distortions

Pseudometric:

$$\{\eta(n)\}_{K_1} = \left\langle C_{K_1} + S_{K_1} + A_{K_1} \cdot \eta\left(L_{K_1}\right), V_{K_1} \right\rangle$$

$$d_A(\eta_{K_1}, f) = \min_{i=1, Q} \left( \max_{n=1, z} \left| \eta(n) - f(n) \right| \right)$$

Magnitude Alternation

Duration alternation

Magnitude Ratio Alternation

Offset relative to isoelectric line

Presence of slow trend
Template matching – 1

\[
X_{K_1} = \begin{bmatrix}
X_1 \\
X_2 \\
\vdots \\
X_M
\end{bmatrix}
= \begin{bmatrix}
x_{11} & x_{12} & \cdots & x_{1N} \\
x_{21} & x_{22} & \cdots & x_{2N} \\
\vdots & \vdots & \ddots & \vdots \\
x_{M1} & x_{M2} & \cdots & x_{MN}
\end{bmatrix}
\]

\[
C_{K_1} = \begin{bmatrix}
c_{11} & c_{12} & \cdots & c_{1N} \\
c_{21} & c_{22} & \cdots & c_{2N} \\
\vdots & \vdots & \ddots & \vdots \\
c_{N1} & c_{N2} & \cdots & c_{NN}
\end{bmatrix}
\]

\[
\ell_{K_1} = \max_{k=1}^{N} (|\lambda_k|)
\]

\[
\eta_{K_1} = [\eta_1, \eta_2, \ldots, \eta_N]
\]

\[
c_{ij} = \frac{1}{M} \sum_{k=1}^{M} x_{ki}x_{kj}
\]

\[
\det \left(C_{K_1} - \lambda I\right) = 0
\]

\[
C_{K_1} \nu_k = \lambda_k \nu_k
\]

\[
C_{K_1} \eta_{K_1} = \ell_{K_1} \eta_{K_1}
\]

Main eigenvector keeps the most information about member’s prevailing and dominating properties.
Template matching – 2

Duration: \[ \eta_{K_1}^L (n) = \eta_{K_1} (l \cdot n), \quad l > 0, \quad L_{K_1} = \{ l_i \}_{i=1}^{I_{K_1}} \]

Magnitude: \[ \eta_{K_1}^A (n) = a \cdot \eta_{K_1} (n), \quad a > 0, \quad A_{K_1} = \{ a_j \}_{j=1}^{I_{K_1}} \]

Offset: \[ \eta_{K_1}^S (n) = s + \eta_{K_1} (n), \quad S_{K_1} = \{ s_k \}_{k=1}^{I_{K_1}} \]

\[ \eta_{K_1}^T (n) = T_p (n) + \eta_{K_1} (n), \]

Trend: \[ T_p (n) = c_0 + c_1 n + c_2 n^2 + \ldots + c_p n^p \]

\[ C_{K_1} = \left\{ C_{m_{K_1}} \right\}_{m=1}^{I_{m_{K_1}}}, \quad C_{m_{K_1}} = \left\{ c_{mr} \right\}_{r=1}^{J_{m_{K_1}}} \]

Magnitude Ratio: \[ V_{K_1} = \left[ v_{1K_1}, v_{2K_1}, \ldots, v_{N_{K_1}} \right], \quad v_{qK_1}, \quad q = 1, N, \]

\[ v_{qK_1} = \left\{ v_{b_{K_1}} \right\}_{b=1}^{I_{b_{K_1}}} \]
Template matching – 3

TP – 85%
FP (while all diagnostically meaningful complexes are detected) – 15%
Sensitivity – 82%
Selectivity – 72%

Percentage $P$ of TP (○) and FP (□) from threshold $d_A$
Template matching – 4
Template matching – 5
Template matching – 6
Template matching – 7
Seizure prediction and prevention – 1

- Neurostimulator
- Simulator control
- Multiparametric data analysis system
- Classification and prediction
Seizure prediction and prevention – 2

**Signal analysis tasks:**

1. Feature extraction from EEG and/or ECG.
2. Linear/nonlinear analysis and coupling estimation.
5. Generation of signals for direct brain tissue stimulation.
Neurostimulator with Feedback
Permutation Entropy

PE is a descriptor of time series complexity, unpredictability, disorder, chaoticity, nonlinearity and stochasticity and can reflect complex nonlinear interconnections between anatomical and functional subsystems emerged in brain in healthy state and during various diseases.

\[
p(\pi_j) = \frac{q(j)}{N - (m-1)l}
\]

\[
PermEn_{\text{norm}}(m,l) = -\frac{\sum_{j=1}^{m!} p(\pi_j) \log p(\pi_j)}{\log m!}
\]
PE saturates starting from some lag value, different for various signal types.

PE as a function of time lag and order for tree types of EEG signals.

Permutation Entropy averaged values for 5th order for different combination of lags and downsampling factor.
PE for seizure prediction

EEG Signal # 2

PermEn of order m=3
Interhemispheric Interactions

- **Left**: mostly analytics (speech, input signals), telic actions,
- **Left** hemisphere is mainly responsible for speech
- **Right**: interaction with environment automatic actions, shape, distance and space perception. Signing!
- People with **right** hemisphere injuries have difficulties with perception, orientation, memory, face recognition and attention.
- **Natural opposition**, like sense-intuition, science-art, logic-mystics.
Synchrony and Symmetry of brain functioning

It is known that the electrical brain activity is more or less synchronous in two hemispheres. 

Symmetry is not exact but is highly essential for healthy brain.

Spatial characteristics of brain activity:
- Rhythm distribution between zones – areas of dominant activity;
- Symmetry of bioelectric activity – similarity of oscillation parameters (e.g. magnitude and frequency content) in different hemispheres.

Applications of interhemispheric symmetry estimation:
- Response to functional tests, rhythm assimilation (hyperventilation, photostimulation etc.);
- Right- left-handed persons research;
- Dynamics of activity propagation, dispersion, penetration and entrapping;
- Pathological changes in symmetry (amplification or attenuation of differences);
- Epilepsy research (seizures etc.)
Symmetry experiment setup

asymmetric leads

symmetric leads
Phase-Locking Value

\[
PLV = \frac{1}{N} \left| \sum_{n=0}^{N-1} e^{i(\varphi_y(nT) - \varphi_x(nT))} \right|
\]

\[
SPLV(f,t) = \left| \frac{1}{\delta} \int_{t-\delta/2}^{t+\delta/2} \exp(\Delta f_y(f,\tau) - \Delta f_x(f,\tau)) d\tau \right|
\]

**Averaged synchronization**

<table>
<thead>
<tr>
<th></th>
<th>Healthy EEG</th>
<th>Epileptic EEG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symmetric</td>
<td>0.22 ± 0.04</td>
<td>0.12 ± 0.02</td>
</tr>
<tr>
<td>Asymmetric</td>
<td>0.10 ± 0.01</td>
<td>0.03 ± 0.02</td>
</tr>
</tbody>
</table>

- In application to evaluation of degree of symmetry between two hemispheres in EEG of healthy people and in the presence of epileptiform activity, significant difference was shown, and thus it could potentially be an important clinical diagnostic tool.

- EEG phase synchronization for main clinically meaningful bands was analyzed for healthy subjects and the difference between synchronization in symmetric and asymmetric channels was shown with high validity according to the Kruskal-Wallis criteria (p≤0.001) in all frequency bands.
Synchronization for healthy brain

• EEG phase synchronization for main clinically meaningful bands was analyzed for healthy subjects and the difference between synchronization in symmetric and asymmetric channels was shown with enough validity according to the Kruskal-Wallis criteria.

1. Kolmogorov-Smirnov test (non-normal, p=0.05)
2. Kruskal-Wallis (distributions with equal means), existence of synchronization was validated at p≤0.001 (for gamma (p≤0.05 ))

1, 2 and 3: symmetric, symmetric channels and surrogate signals
Brain-Computer Interface

- **Brain–computer interface (BCI)** is a direct communication pathway between the human brain and an external device.
BCI system

Signal acquisition
- EEG
- ECoG
- LFP
- SU

Signal processing
- Autoregressive
- Wavelets
- Fourier transform
- Laplacian filter
- Common spatial filters
- Others

Effector device
- Robotic arms
- Wheelchairs
- Cursors
- Spellers
- Others

Diagram showing the flow from signal acquisition, through signal processing, to an effector device.
OpenBCI Project

A customizable and fully open brain-computer interface platform that gives you access to high-quality brain wave data.
BCI for WoW

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