Digital EEG
From Basics to Advanced Analysis

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Learning Objectives

• Understand the basic principles in digitizing the EEG
• Understand the strengths and limitations of screen display
• Understand digital filters
• Understand the basics of spectral analysis
• Understand spatial sampling, topographic mapping and basics of dipole analysis
Disclosure

• Former major shareholder, Stellate
Digitizing the EEG

• Digitizing is performed by sampling the continuous signal at regular and small intervals
• How small should the intervals be to ensure a faithful representation of the signal?
• The sampling theorem states that no information is lost in the sampling process if the sampling rate is at least twice the highest frequency in the signal
• In theory, if a signal includes frequencies up to 100Hz, then sampling at 200Hz will ensure a perfect representation of the signal
• Half the sampling frequency is called the Nyquist frequency.
Digitizing the EEG

• How does the sampling theorem applies to the EEG?
  – The only way to define a frequency above which there is no signal is by applying an analog low-pass filter
  – No analog filter has a perfect cut-off frequency
  – With a 4-pole low-pass filter at 70Hz, most activity above 100Hz is eliminated, and sampling at 200Hz (every 5ms) is justified.
  – One usually needs a filter at 1/3 the sampling rate (to study activity up to 700Hz, a 700Hz filter and a sampling rate of 2000Hz are needed).
Digitizing the EEG

• What are the consequences of not respecting the sampling theorem?
  – The digitized signal does not represent the original analog signal and it is impossible to recover the original signal
  – This distortion is caused by aliasing, the representation of activity above the Nyquist frequency at values below the Nyquist frequency.
• The anti-aliasing filter must be an analog filter and must operate before digitizing
• The higher the sampling rate, the higher the storage requirements.
Aliasing

5 Hz wave

9 Hz sampling

7 Hz sampling
Digitizing the EEG:
Sample Precision

• 12-bit sampling, 16-bit sampling, 20-bit sampling?

• 12 bits \((2^{12}, 0 \text{ to } 4095)\)
  – Represents numbers between -2048 and +2047
  – If 1 unit represents 1µV, then 12 bits can represent values between -2mV and +2mV
  – This is sufficient for most EEG situations

• 16 bits
  – Represents numbers between -32,000 and +32,000
  – If one unit represents 0.25µV, then 16 bits can represent values between -8mV and +8mV
  – This is more than enough for any EEG application, including intracerebral EEG.
EEG Display: Screen Issues

- A typical modern computer screen has a resolution of 1000x1400
- If the EEG is sampled at 200Hz, a width of 1400 pixels allows the display of 7 seconds of EEG
- If one wants to display more than 7 seconds, it is not possible to display all digitized data: some data must be discarded or distorted
- There are different methods to deal with the time scale issue
- Similar situation with the amplitude scale; it would require a screen with 4000 vertical pixels to see with full precision one channel sampled with 12 bits and fluctuating between -2mV and +2mV (values fluctuating between -2000 and +2000)
2 seconds

10 Hz

70 Hz
10 seconds

10 Hz

70 Hz
Digital Filtering

• After the EEG has been digitized, it is possible to filter it with digital filters, which are computer programs. There are low-pass, high-pass, band-pass, and band-reject filters.

• There are two basic types of digital filters:
  – Infinite Impulse Response (IIR) filters. They are fast but result in distortions similar to those generated by analog filters.
  – Finite Impulse Response (FIR) filters, which can be designed without any distortion, but require more computing power.
  – Given the power of modern computers, FIR filters are preferable, but are not always possible.
2 Hz and 30 Hz signal
High pass IIR filter at 1 Hz, order 2
2 Hz and 30 Hz signal
High pass IIR filter at 3 Hz, order 2
2 Hz and 30 Hz signal
High pass IIR filter at 5 Hz, order 3
7 Hz and 30 Hz signal
Low pass IIR filter at 20 Hz, order 3
7 Hz and 30 Hz signal
Low pass FIR filter at 27 Hz, order 11
7 Hz and 30 Hz signal
Low pass FIR filter at 25 Hz, order 63
Spectral Analysis

- Fourier theorem: *It is possible to represent any stationary time series with a sum of sinusoids at different frequencies and with different amplitudes and phases*
- The spectrum of a signal is a representation of the amplitude of the sinusoids necessary to represent the signal
- *This mathematical transformation does not imply that the brain generates sinusoids*
- The interpretation of spectra is particularly tricky when the signal includes rhythmic but non sinusoidal activity (i.e. sharp alpha activity).
- Spectral analysis is useful to *quantify* different aspects of the EEG.
Quantification: the surface of the alpha band measures the energy in this band.
Spatial Sampling: how many Electrodes?

- Very difficult to determine the absolute requirements because of impossibility to record simultaneously and broadly the scalp and intracerebral EEG
- Clinical studies usually record with 25 to 30 electrodes: important events are probably not missed
- For correct sampling of the complete scalp field without loss of information, 64 to 128 electrodes may be necessary
- Significant practical problem.
The 10/20 System
Electrode localization
The 10/10 System
When does adding electrodes stop adding information?

Lantz et al, Clin Neurophysiol 2003
Adding electrodes does not remove the limitations of scalp EEG: 10cm$^2$

Tao et al, Epilepsia, 2005
The limitations of scalp EEG: $13cm^2$

Tao et al, Epilepsia, 2005
The Scalp EEG and High Frequencies

- It is often said that the skull filters high frequencies.
- In fact, the skull does not filter any electrical activity up to 10,000 Hz.
- All cortical EEG activity is transmitted from the brain to the scalp equally.
- High frequencies are rarely seen on the scalp because their generator usually has a small spatial extent.
- If high frequency activity occurred over a wide extent, it would be seen on the scalp as much as low frequencies such as delta.
Dipole Analysis

• It is sometimes possible to approximate a distribution of potential on the scalp with a distribution generated by a point dipole located in the brain.
• This dipole is therefore a possible source for the observed potential distribution. It is no the necessary source as there are multiple other source configurations that can lead to the same scalp distribution.
• Dipole modeling can be useful to find the source of potentials that can reasonably be assumed to be generated in a very small volume.
• If such an assumption cannot be made about a source, then dipole modeling is merely a mathematical representation, which may bear little resemblance to reality.
The Dipole Model: Calculations

- Place a dipole at a random location inside the brain.
- Solve the *forward problem* for this dipole: compute the scalp distribution resulting from this dipole.
- Compare the scalp distribution resulting from the dipole to that *measured* on the scalp (the EEG).
- Make an iterative search for the dipole that will result in the smallest possible difference between its distribution and the real EEG.
- Because the scalp distribution is a non-linear function of dipole parameters, this is a non-linear optimization search with a risk of falling into local minima (search strategy should include different starting points).
Geometric Model of the Brain Surface
Non-invasive localization of hand area

Anatomical marking

Dipole model of SEP
Can the Dipole Model be Misleading?

- YES
- In most instances, it is possible to find a dipolar source that can model well a scalp distribution. This only indicates that the dipole is a possible source of the distribution. It does not prove that it is the source of the distribution.
- The goodness of fit of the model is not a proof, not even an indication of its validity.
- There are systematic errors caused by the fact that the source is likely to have a significant spatial extent.
Simulation of extended source and dipole model

Large bifrontal source of large but realistic amplitude including (M: 120 cm$^2$) or not (N: 90 cm$^2$) a mesial section

All 20 realizations of the source yield dipole models with a consistent deep source

K. Kobayashi et al, *Epilepsia* 2005
Dipole Models of Epileptic Spikes: Direction informative – Location uncertain

Ebersole et al, J Clin Neurophysiol 2007
Dipole Models of Epileptic Spikes: Direction informative – Location uncertain

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<thead>
<tr>
<th>Electrode</th>
<th>Timing (ms)</th>
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<tr>
<td>F9 - avr</td>
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<tr>
<td>M2 - avr</td>
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Ebersole et al, J Clin Neurophysiol 2007