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The Computerized EEG

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ÖZET

Bilgisayarlı EEG

Bilgisayarlı EEG terimi beyin aktivitesinin bilgisayar sistemine dayalı olarak kaydı, dökümü ve depolanmasını ifade eder. Bu sistem sıklıkla EEG değerlendirmesi için kulanılan bir veya daha fazla çalışma merkezine yerel bir veya birden fazla PC şebekeleri ile bağlanarak oluşturulur. Birinci bölümde dijitizasyonun avantajları, analogdan dijitale dönüştürme işlemi, örnekleme (Nyquist'in teoremi), nicelleştirme, sinyalleri depolama ve dökümünü elde etme konuları kısaca tartışılacaktır. Dijitizasyondan önce EEG sinyallerinin tanınabilir hale gelmeleri için, amplifikasyon ve düşük-geçişli süzme işlemlerinin gerçekleştirilmesi gerekir. İkinci bölümde ise, epileptiform geçici dalgaların saptanması, spektral analiz, jerk-locked ortalama ve haritalama için değişik yöntemleri de içeren çeşitli EEG otomatik analiz tipleri gözden geçirilmiştir.

Anahtar kelimeler: *bilgisayarlı EEG, A/D dönüştürme, Nyquist'in teoremi, aliasing, otomatik analiz*

SUMMARY

The term computerized EEG refers to the recording, displaying and storage of the brain activity by means of a computer-based system, usually a local network of PCs for EEG recordings connected to one or more graphical workstations for EEG review and analysis. In the first section, the advantages of the digitization and the process of analog-to-digital conversion, the sampling (Nyquist's) theorem, quantization, signal storage and display are briefly discussed. Preparation of the EEG signal before digitization includes amplification and analog low-pass filtering in order to avoid the aliasing effect. In the second section, several types of automatic analysis of the EEG are reviewed, including different methods for epileptiform transient detection, spectral analysis, jerk-locked averaging and mapping procedure.

Key words: *computerized EEG, A/D conversion, Nyquist's theorem, aliasing, automatic analysis*

INTRODUCTION

The term computerized EEG refers to the recording of the brain activity obtained by a computer-based system.

EEG data picked-up by scalp electrodes are amplified and filtered then they are converted into a digital form to be feeded on a computer devoted to data acquisition. Review can take place on the same computer or on a workstation server of a local or remote network, to which the digital data are transmitted to. The workstation is equipped to allow the reconstruction of the orginal signal for visual inspection and to perform further automatic analysis (1,2).

There are **several advantages** in using a computer system to record EEG activity in comparison with a "traditional" polygraph:

1) The digital data can be permanently stored in a very compacted format on a convenient support from which the original recording can be suitably retrieved at will.

2) EEG traces are reviewed on a "high-definition" computer screen, and only selected segments can be printed, thus reducing the use and handling of paper.

3) Time and/or amplitude can be retrospectively rescaled.

4) When data are recorded by a referential montage different montages can be reconstructed from the same recording sample.

5) Data can be digitally filtered at different cut-off frequencies.

6) Several methods of automatic analysis can be applied on the same EEG traces.

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On the other hand it is mandatory that computer-based electroencephalographs must not sacrifice any of the fundamental capability of the traditional EEG machine. It is to bear in mind, in fact, that the manipulation of the signal necessary for computer acquisition, if not controlled properly, could introduce errors and artifacts in signal appearance and/or distortion of the original waveforms.

In order to exploit the advantages and the power of a computer, the system should make possible to:

- entry of patient information properly associated with EEG traces, to allow fast and easy data retrieval
- reformat montages and adjust the horizontal and vertical display scales
- be connected with electronic or integrated devices for impedance checking, calibration and photic stimulation
- perform automatic notation of recording parameter changes
- allow on-line or retrospective annotation, marking, EEG epoch selection and time measurements by means of cursors
- display continuous multichannel EEG on and off-line
- modify the number of displayed channels
- perform high speed searching and navigation
- employ standard network hardware interface and software protocols
- obtain optional synchronization with video recording for EEG/video monitoring of epileptic seizures
- perform further signal analysis, such as topographic mapping and spectral analysis.

The next section will deal with the proper procedures for analog-to-digital conversion, storage and to digital-to analogic conversion for displaying of the EEG signal. A further section will be devoted to the most common methods of automatic analysis.

Acquisition, storage and display of computerized EEG

Data acquisition

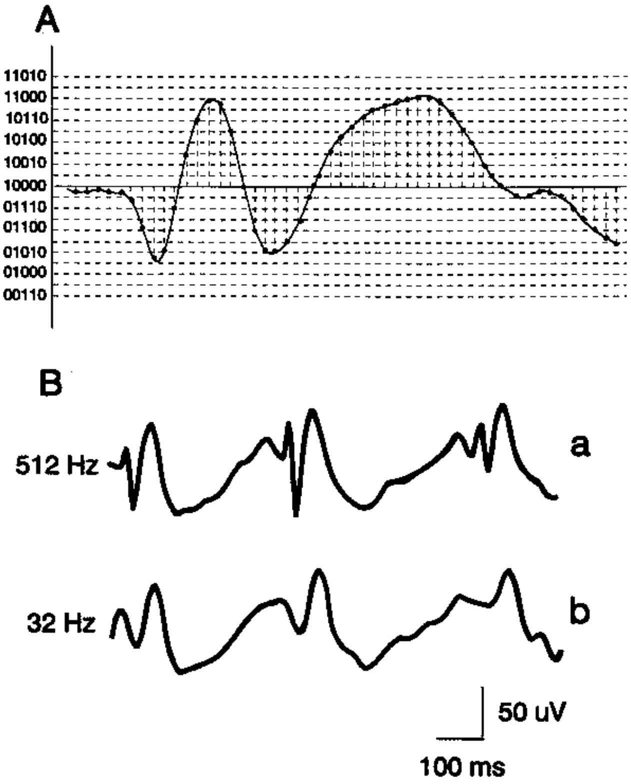

FIG. 1

Fig. 1A. A/D conversion of the continuous EEG signal is performed by sampling the voltage at equidistant time intervals and digitizing their amplitudes according to the corresponding quantizing levels.
Fig. 1B. The same EEG waveform sampled at two different frequencies. When the sampling rate is below the half of the frequency content of the signal aliasing occurs (trace b).

The operation by which an analog signal such as the EEG is entered in a computer is the analog-to-digital (A/D) conversion whereby a continuous voltage is transformed into a set of integer values by measuring the analog signal amplitude at discrete equidistant time intervals dt (sampling procedure) and converting the measured voltage to a finite integer digital form, according to corresponding amplitude levels (quantization) (Fig. 1A).

For a correct A/D conversion the sampling rate (=1/dt) must be at least two times the higher frequency (Nyquist frequency) contained in the analog signal (Nyquist's theorem). When the continuous waveform is correctly sampled it can be exactly reconstructed using a sinusoidal interpolation function. On the contrary, when the sampling rate is too low, aliasing occurs, that is frequencies higher than half sampling rate appear as lower frequencies, causing a distortion of the original waveform. This error cannot be corrected after A/D conversion (Fig. 1B) (3).

In order to avoid aliasing all frequency components above half of sampling rate must be filtered by low-pass filtering prior to digitazion.

The resolution of the digitazion depends on the number of bits of the A/D converter.

An A/D converter usually produces a digital value with a minimum of zero and a maximum which depends on the resolution. It is possible to calculate this maximum value with the following formula:

$\text{value}_{\text{max}}=2^N-1$, where N=number of bits.

For example, for a 12 bit A/D converter the numerical output ranges between 0 and 4095.

With this information and a given full-scale input range, it is possible to calculate the voltage resolution. Assuming an input range of ±5V, then with a 12 bit A/D converter the voltage resolution is 10/4096=2.44 mV.

In order to represent the EEG with a good resolution the amplitude of the highest waves to be recorded must extend over most of the output numerical range of the A/D converter. If this does not occur, the signal is to be amplified (signal conditioning) before conversion, otherwise one has to modify the input range of the A/D converter.

In practice, to avoid this risk, a computer-based system might include the following characteristics:

- accurate resolution both on time (sampling frequency suitable to polygraphic recording, ranging between 128 and 1024 Hz at least) and display (1024x768 pixels or better).

- ability to modify recording parameters (high and low cut-off frequencies, amplifier setting), to change montages and to adjust the horizontal and vertical display scales.

Data storage

In a network based system, with several recording and reviewing units, the file registration and retrieving functions are critical components.

Users from different location must be able to rapidly search, select and access EEG records from the list of available patients, and perform file and label manipulation (e.g. copy, move and delete commands).

EEG records can be temporarily or permanently stored on hard disks. They usually consists of one or more metal platters coated with a magnetizable material, stacked in a "disk pack" that can be permanently fixed in place or removed from the disk drive; data are stored on concentric tracks. Disks are read and written by a movable arm supporting a conducting coil named the head, which reads/writes patterns of magnetic flux change from the rapidly spinning disk. Hard disks with high storage capacity (500-1000 MByte) with fast access and data transfer times and relatively low prices are now currently available.

Write-once read-many (WORM) removable optical disk can store more than 1000 MByte (1 GByte) of data, they do not deteriorate with time and provide a very attractive and efficient solution to the permanent archiving of the large volume of EEG data (about 250 Kbyte/min of data in the case of a 16 channel EEG recording digitized at a sampling frequency of 256 Hz, with a 8-bit A/D converter).

The WORM disk is easly written by means of a low-powered laser which burst preformetted blisters; during the read operation a laser illuminates the disk's surface and the burst blister are recognized from the surrounding area by an electronic device.

Signal display

In a computerized EEG system the standard output device is usually a monitor. For a good representation of the EEG traces the minimal value of the display resolution is 1024 horizontal x 768 vertical dots (Super-VGA), but monitor with higher resolution are now available (e.g. 1280x1024). The appearance of digital data should be similar to that of conventional paper EEG; care must be taken to reproduce conventional time bases, filters and gain (sensitivity).

A single screen may be used to display the EEG traces, program "menus" and other functions, but a better solution, particularly when a great number of EEG channel are to be displayed, is to use two separate monitors, one of which devoted exclusively to the EEG representation.

The capability to mark and label specific part of EEG records is a critical function; the technologists and physicians must be able to highlight important

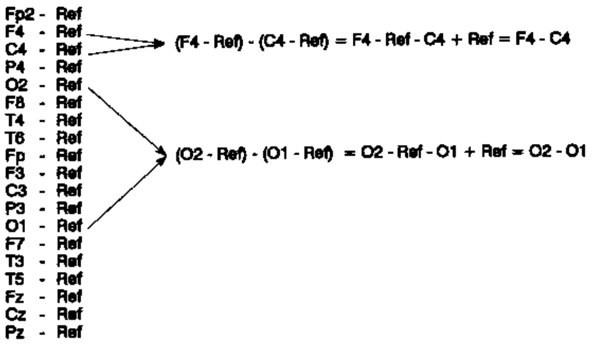

FIG. 2

Fig. 2. Example of montage reformatting. EEG traces are recorded from 19 electrodes connected to a common reference electrode. The algebraical subtraction of the voltage from any two derivations (e.g. F4-Ref and C4-Ref) results in the voltage like that observed whether the two active electrodes were connected in a bipolar derivation.

electroclinical events and to retrieve and access them rapidly.

One of the main advantages of the computerized EEG is that the pattern of activity can be displayed in different montages taking advantage from the possibility of a mathematical reformatting of montages.

An example will best serve to explain this process of reformatting. An EEG is recorded using a referential montage (Fig. 2) in which traces from the scalp electrodes are taken with respect to a common electrode. If now, the voltages from two of these derivations, say F4 and C4, are subtracted algebraically over time, the result would be a time-varying voltage like that observed if F4 and C4 were connected in a bipolar derivation.

The same operation can be carried out from any pair of electrodes, and in this way a wide variety of montages can be created.

In pratical terms, this procedure allows the technician to record the EEGs using only a single montage. Later, when the record is read, the electroencephalographer can reformat the same EEG activity into any number of different montages.

Automatic Analysis

Methods of EEG analysis can be divided into two basic categories, parametric and non-parametric. In the first case the EEG signal is assumed to be generated by a specific model which is characterized by a set of coefficients or parameters. Another common categorization is based on the definition of frequency versus time domain methods, although methods classified in the frequency (e.g. power spectra) or time domains are actually closely related (4,5,6).

One of the first applications of computational techniques to EEG signal was aimed at extracting features and quantifying information duplicating the logical process of the human analysis (mimetic techniques).

An alternative approach to automate the EEG analysis was based on the application of generic methods of analysis developed in other fields, such as spectral analysis, parametric identification (Ar modelling), statistical techniques, neural networks (7-11).

Mimetic techniqes include amplitude, interval, zero-crossing and period analysis, peak detection, period-amplitude analysis. These methods usually attempt to assess the background activity and to recognize brief transient activity and are based on algorithms for waveform decomposition (12); their main advantage is of requiring simple computation, but this advantage has lost some importance with the advent of inexpensive powerful computers.

Information from multiple channels over long period of time, temporal changing with different states or pathological process may be analyzed in order to "interpret" the EEG.

Mimetic techniques have been widely applied for detecting epileptiform discharges, because spikes and sharp waves are defined empirically as waves of particular morphology. Which parameters are the best for detecting sharp waves and spikes is still matter of research: most methods are based on combination of sharpness, slope, amplitude and duration measures (13,14).

In order to reduce false positive detections, spatial and temporal information, knowledge-based system, expert-system have been more recently used (15-18).

At present, the approach of the state-dependent spike detection [16,17] is considered more rewarding than theoretically based pattern recognition methods.

"Non-mimetic" methods to detect epileptiform anomalies include inverse filtering, mostly by using autoregressive modelling of the background EEG, correlation analysis and template matched filtering, spectral analysis (Fourier and other mathematical transforms), particularly for the detection of 3Hz spike-and-wave discharges, and discriminant analysis, a statistical technique aimed at providing a classification rule and identifying the parameters that are important for distinguishing between different groups [19].

The correlation analysis [20] measures the degree of waveform similarity between different EEG epochs; it emphasizes the periodic EEG activity and suppress non-periodic components.

Correlation function and power density spectrum can be obtained one from another mathematically by Fourier transformation.

Two widely used techniques of automatic analysis will be shortly illustrated:

Spectral analysis [21]

Spectral analysis performed by Fourier transform is the most common way to quantify the frequency content of the background EEG activity. The Fourier theorem states that any waveform can be considered the sum of a series of sinusoidal functions at different frequencies with different amplitudes. The Fourier coefficients can be quickly computed by means of the Fast Fourier transform algorithm. This requires that the number of EEG samples to be analyzed be a power of 2 (256, 512, 1024, ... points). The maximum frequency of the spectrum is half the sampling frequency, and the frequency resolution, the separation between two consecutive sin waves, is inversely proportional to the duration of the EEG epoch, expressed in sec.

In practice the power spectrum density of a given signal is obtained, applying a discrete Fourier transformation to the digitized signal x(n), as follows

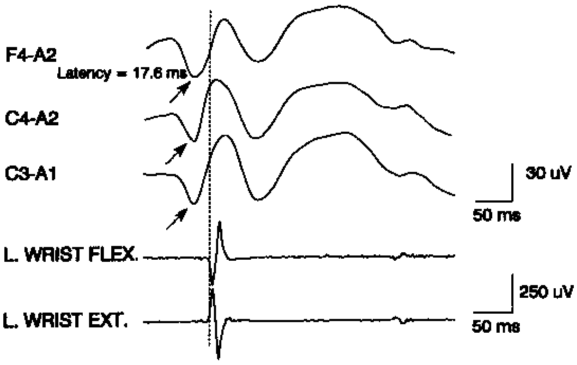

FIG. 3

Fig. 3. Jerk-locked averaging of a 19 year-old female affected by Lafora body disease. A positive-negative potential followed by a large slow wave precedes the spontaneous myoclonic jerk in right arm muscles by about 18 msec.

$$F(i\Delta f)=\frac{\Delta t}{N}\left|\sum_{n=1}^{N} x(n)e^{-j2\pi ni\Delta f\Delta t}\right|^2=\frac{\Delta t}{N}\left|\sum_{n=1}^{N} x(n)e^{-j2\pi ni/N}\right|^2=$$

where, Δt is the sampling interval, N is the number of samples, $\Delta f=1/N\Delta t$, and $i=0,1,\ldots,N/2$

In order to reduce the distortion in the power spectrum (leakage) a common procedure is smoothing the raw digital data, in time domain, or the Periodogram F(i) by means of a window or taper (e.g. Hanning window, partial cosine taper).

The power spectrum for a long EEG section, lasting more than 10 sec is usually obtained by computing the spectra for shorter, possibly overlapped segments of the section, and then averaging, for every frequency, the values of each spectrum [22].

Jerk-locked averaging

Jerk-locked averaging (JLA) or back averaging is a technique aimed at finding out the possible relationship between an EEG transient, such as a spike, a sharp-wave or a spike and wave, and the electromyographic burst of activity associated with a myoclonic jerk [23].

This issue is quite similar to that of extracting an evoked potential from the cortical activity recorded from the scalp, time-related to the evoking stimulus. The main differences between JLA and evoked potential procedures is that in the first case the analysis time include a period before and after the onset of myoclonic jerk and that the time of this event is unknown (Fig. 3).

There are two different ways whereby JLA procedure can be perfomed (23,24):

1) "On-line JLA". By an electronic device which rectifies the EMG activity a trigger signal is produced whenever a preset threshold level is exceeded, then EEG and EMG traces for the selected time analysis are added to the running average.

2) "Computer-assisted JLA". EEG and EMG data are converted to digital form and stored into a computer. A computer program detects the occurrence of a rectified EMG activity which exceed the threshold level and display the corresponding epochs on the screen, then these epochs are reviewed by the user and the accurate onset of the myoclonic jerk is manually defined.

Mapping

Brain mapping refers to the methodology of representing the EEG activity, either spontaneous or evoked, in the spatial domain as a topographic map projected on the scalp. The parameter represented may be an amplitude, a spectral variable, a correlation or statistical measure.

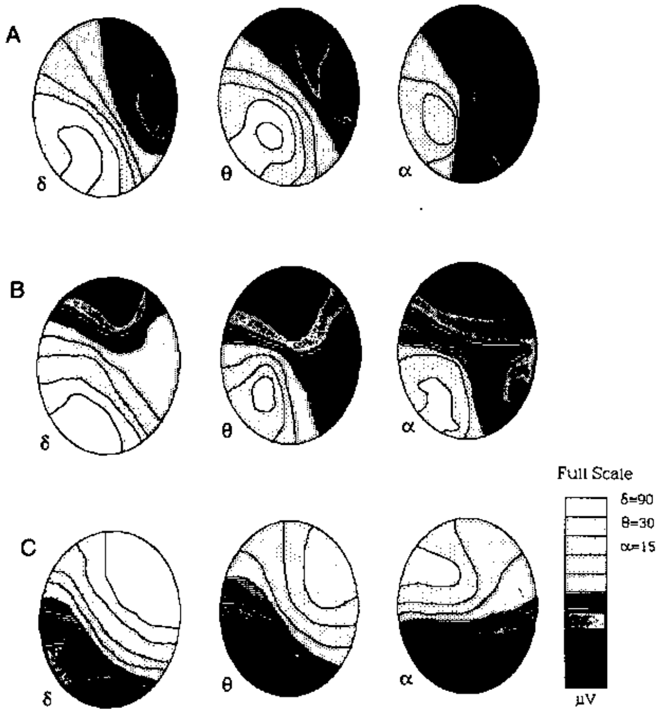

Fig. 4. Effect of the choice of the reference on topographical power maps from a 61-years-old woman with subarachnoid hemorrhage. A) linked-ears reference, B) nose reference, C) cervical reference (from Nuwer MR, 1988).

It is known that an adequate sampling of a signal, either in space or time domain, requires that the sampling rate should be at least twice the highest frequency in the signal (Nyquist theorem); in the space domain this means that the interelectrode distance should be less than half the shortest spatial frequency of the potential distribution. This value is not easy to determine, since it depends on the number and the depth of the generators. From simulations, for a source represented by a single radial dipole located just below the skull (the worst position), the maximal interelectrode distance results about 2.5 cm. Using the international 10-20 system the distance between two adjacent electrodes is about 4.5 cm, and for a 64 electrode montage is 3.2 cm (25).

The choice of the reference electrode affects the appearance of any brain map.

Two different types of EEG recordings can be used:

1) the reference-dependent recording, in which each amplifier is connected with an active electrode and the reference (common) electrode. Because there is no reference point with zero potential, the map is significantly affected by the choice of the reference, therefore different maps will be obtained according to different selected references (Fig. 4) (26).

2) the reference-independent recording, which encompasses common average reference, source derivations and Laplacian operator method. The latter

Fig. 5. Topographical maps of an auditory evoked potential 100 msec after the delivery of the stimulus. The three left maps are obtained using the noise (top), the mastoid (middle) and the average (bottom) reference. The map on the right is the SCD representation of the same evoked potential (from Perrin F, Bertrand O, Giard MH, Pernier, 1990).

one is a mathematical procedure where by the potential at each electrode is converted to a value which represent the current density entering or leaving the scalp at that site. Scalp current density procedure reduces the spatial distortion due to the volume conductor properties of the brain and surrounding tissues, and it is more sensitive to cortical generators than to the subcortical ones (Fig. 5) $^{(27)}$.

Once the EEG is recorded by scalp electrodes, we have to represent the potential distribution on a topographic map for all the (x,y) points of the surface. Since the potential is known only at electrode sites, spatial interpolation between the electrode positions is necessary. For this interpolation, different algorithms can be used, ranging from the N-nearest neighbour electrode algorithm to the sophisticated and computationally complex spline interpolation $^{(26,28)}$.

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