# AN ELECTROENCEPHALOGRAPHIC PROCESSING ALGORITHM SPECIFICALLY INTENDED FOR ANALYSIS OF CEREBRAL ELECTRICAL ACTIVITY

*Thomas K. Gregory, PhD, and Daniel C. Pettus*

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**ABSTRACT.** This article describes a computer procedure for the examination and analysis of cerebral electrical activity (CEA). Changes in CEA generate random electrical activity and may include transitory events, such as burst episodes. As yet, there are no standard techniques for evaluating the statistical process of the CEA. This article proposes a computerized method of analyzing the stochastic character of CEA using a computer algorithm. Using a real-time wave-by-wave technique, the algorithm characterizes CEA by the frequency and amplitude of each CEA waveform. This algorithm produces digital packets of information that describe individual CEA waveforms.

**KEY WORDS.** Monitoring, physiologic; electroencephalography. Brain: electroencephalography. Algorithm: aperiodic analysis.

The ELECTROENCEPHALOGRAM (EEG) is a record of the CEREBRAL ELECTRICAL ACTIVITY (CEA) and is used to monitor neurological events occurring near the surface of the brain [1]. Observed changes in CEA can provide important information for patient assessment and can alert clinicians to perform appropriate interventions, thus reducing the risk of brain impairment. Unfortunately, the complexities of operation and the difficulty of interpreting the tracings have, in the past, prevented the consistent use of EEG devices in most operative procedures.

The absence of recurring patterns in CEA waveforms considerably complicates their analysis. FOURIER ANALYSIS techniques, which are commonly used in many instruments to transform CEA waveforms into more meaningful displays, do not provide the observer with ideal indications of patient status.

This article describes an algorithm for the analysis of the STOCHASTIC phenomenon of CEA. This algorithm processes stochastic signals in a manner that allows rapid and accurate evaluation of brain status. The algorithm determines, on a wave-by-wave basis, the amplitude and period of each CEA signal. Line frequency interference ARTIFACTS are rejected and electromyographic interference and electrocautery artifacts are detected. In our application, the processed EEG information produced by this algorithm is then presented graphically to the user in several easy to interpret formats [2].

## PROBLEM

CEA can be recorded by using small electrodes attached to the scalp. The variations in electrical potential at the

From Neurometrics, Inc, 5720 Oberlin Dr, San Diego, CA 92121-1723.

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Address correspondence to Dr Gregory.

scalp are reflections of the sum of synaptic potentials (potential differences) generated by neurological events. These signals vary in frequency and amplitude with most pathological changes in the subject's physiologic state. The process of extracting diagnostic information from these electrical signals has traditionally been the specialty of the trained electroencephalographer. These specialists recognize in the recorded EEG signal the waveforms and patterns that indicate patient status [3].

Since the 1930s, several methods have evolved for reducing the amount of information presented in the EEG and simplifying the interpretation of these complex waveforms. First, analog signal processing techniques were used to extract features that appeared to characterize the patient's state. A recurring approach was simply FILTERING the EEG to remove all but a selected range of frequencies. Zero crossing [4], relative power [5], amplitude envelope [6], and other techniques have also been used. As digital computers have become available, their computational power has been applied to assist in processing EEG data.

A principal obstacle in analyzing EEG signals is contending with their random, nonperiodic nature. The filtering of particular frequency ranges by analog techniques is giving way to equivalent digital analysis based on the FAST FOURIER TRANSFORM (FFT). Although the FFT may be used to obtain a spectral representation of the EEG, it is not optimal because of the stochastic nature of the EEG signal and the finite time of the FFT window (EPOCH) during which data are collected. Attempting enhancement, by using techniques called windowing, averaging, smoothing, and other methods, alters the accuracy and resolution of the resultant frequency spectrum [7].

Short-duration waves (waveform components) of relatively large amplitude that contain little energy are difficult to appreciate by using FFT methods. However, the presence of these waves may be highly important [8].

## SOLUTION

The algorithm described here was designed specifically for the analysis of CEA signals. Invented by M. C. Demetrescu, a neurophysiologist at the University of California, Irvine, this algorithm, called the APERIODIC ANALYSIS METHOD, responds to rapid changes in EEG signals that result from variations in the physiological state of a subject [9].

The system is currently implemented with multiple patented methods on the Lifescan EEG monitor (Neurometrics, Inc., San Diego, CA). The Lifescan EEG monitor contains two independent subsystems. The front-end subsystem converts analog CEA signals into a set of digital parameters by means of the algorithm. The color graphics subsystem graphically displays the processing result on a color cathode ray tube.

The algorithm analyzes local extremes in unprocessed CEA waveforms. For each peak and valley, the voltage amplitude (height of a detected CEA signal peak or valley) and the time of occurrence are measured. The algorithm then extracts wave amplitude and frequency from these data and presents the information to the graphics subsystem.

By this method, a wave is defined as a fluctuation in voltage that occurs between two local minima in voltage. Thus, the algorithm begins to scan through time for a series of decreasing voltages. When an increase in voltage is noted relative to the previous time point, the previous time and voltage values are noted to represent a local minimum (valley v1). The algorithm then scans through time as long as voltage values increase. A decrease in voltage is noted relative to the previous time point and the previous time and voltage values are noted to represent a local maximum peak (P). The algorithm once again scans through time, searching for the next local minimum (valley v2). This set of voltage fluctuations describes a wave as illustrated in Figure 1. The amplitude of the wave is defined as the average of the difference in voltage between P and v1 and the difference in voltage between P and v2. Thus,

$$\text{amplitude (in microvolts)} = [(V_P - V_{v1}) + (V_P - V_{v2})]/2.$$

The frequency of the wave is defined as the inverse of the difference in time between the occurrence of local minima v1 and v2. Thus,

$$\text{frequency (in hertz)} = 1/(t_{v2} - t_{v1})\ \text{Hz}.$$

To detect the simultaneous occurrence of slow CEA waves (delta or theta waves) in the presence of a high-frequency CEA wave, *slow-wave* and *fast-wave* detection procedures are executed inside the algorithm. The fast-wave method is the basic algorithm just described. The slow-wave method is similar, except that it detects the largest valleys and peaks between zero voltage crossings. Figure 2 shows how the positive peaks and negative valleys are defined.

In addition to detecting and characterizing CEA waves, the algorithm contains several artifact detection and rejection routines. These routines detect the most common kinds of CEA artifacts in the operating room: artifacts harmonically related to the power line frequency, those caused by electromyography, and those with large amplitudes, as compared with the amplitudes

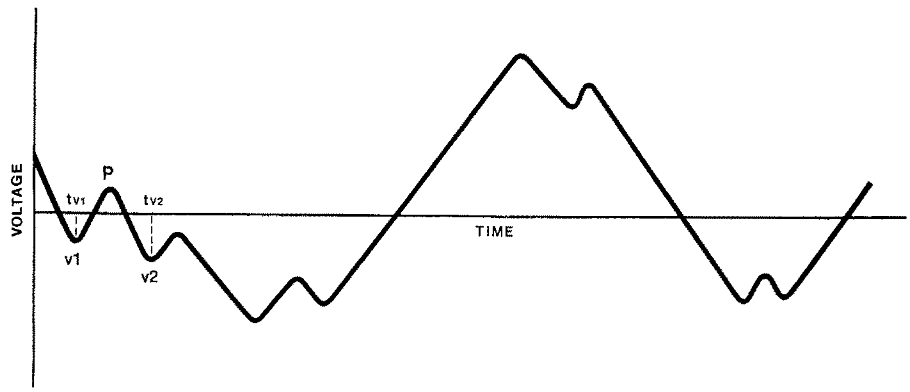


*Fig 1. Fast-wave definition. P = peak; v = valley.*

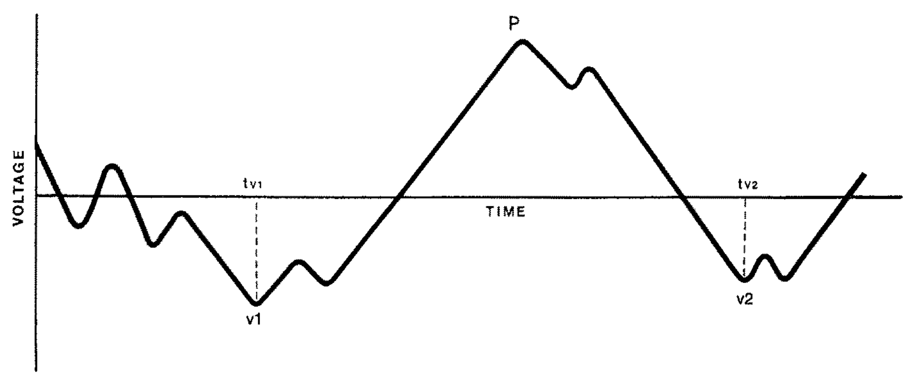


*Fig 2. Slow-wave definition. P = peak; v = valley.*

on a normal EEG. The method of wave analysis allows detection of artifact noise, such as muscle tremor, outside the CEA frequency band because of the high sampling rate required by this type of algorithm.

## DETAILED DESCRIPTION

The algorithm samples EEG signals and passes the resultant digital data through a series of subroutines. Fundamental tasks include: removal of 60-Hz noise, DC offset adjustment, slow-wave and fast-wave detection, and artifact detection and rejection.

The hardware incorporates an eight-bit analog-to-digital converter for each EEG channel. Each channel samples the signal 960 times per second in phase with the AC power source.

The first processing step is removal of 60-Hz noise. Because the analog-to-digital sampling system is PHASE LOCKED to the 60 Hz of the incoming AC power, 60-Hz line interference is removed from the acquired data. This is done by storing these data in a 16-element RING BUFFER and producing the filtered data point as each point is stored.

The filtered data are next sent through a nominal 30-Hz low-pass digital filter. This filtering procedure is a smoothing process using the MOVING BLOCK AVERAGING technique.

The resulting digital values are then passed on to the fast-wave and slow-wave detection procedures. Each detection procedure is performed independently of the other and is responsible for building an information data packet that is sent to the graphics subsystem. The fast-wave routine detects signals from 8.0 Hz to 29.9 Hz. The slow-wave routine detects signals from 0.5 Hz to 7.9 Hz. Before the digital image is sent through the slow-wave routine, it is passed through a nominal 10-Hz filter. This filter routine is similar to that for the nominal 30-Hz filter.

Figure 3 shows the flow of the algorithm. Figure 4 shows the effects of the nominal 30-Hz and nominal 10-Hz filters.

Information packets are sent to the graphics display subsystem each time a wave is detected. If a wave detection takes place on the boundary of a screen update, the

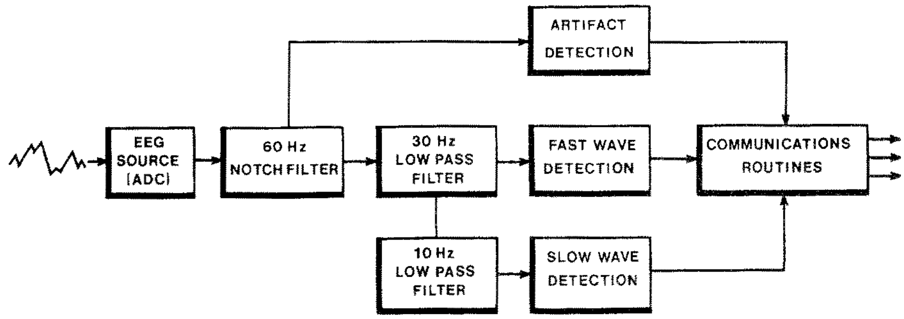


*Fig 3. Aperiodic algorithm flow. EEG = electroencephalogram; ADC = analog-to-digital converter.*

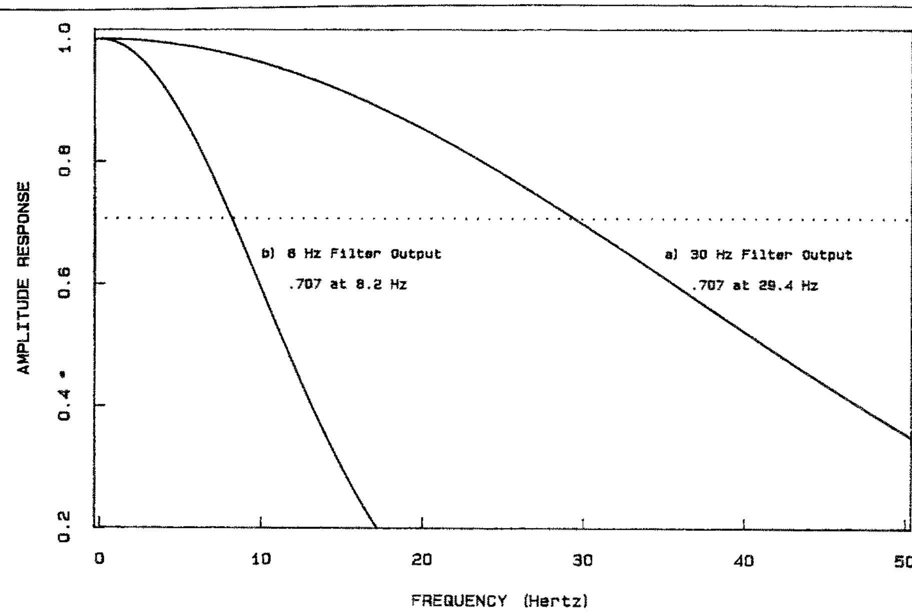


*Fig 4. Plots of amplitude response (in decibels) versus frequency (in Hertz) for (a) the two-pass 30-Hz filter and (b) the two-pass 30-Hz filter followed by the two-pass 8-Hz filter. If we assume the input signal frequency content is flat over the frequency range plotted, the amplitudes in the filter outputs will be as shown.*

information is placed into the later update. Packets for fast waves, slow waves, or fast and slow waves combined, can be sent to the graphics subsystem in one transmission. Each transmission includes the following information: hemisphere identification (left or right), period of wave (33 to 2,000 ms), peak-to-peak amplitude of the wave (1 to 400 μV), wave status (type of artifact, if any), and scalp-electrode impedance.

The amplitude and frequency information is displayed on a color cathode ray tube. By isometric projection, three dimensions are represented on the two-dimensional screen. A vertical colored vector is drawn on the cathode ray tube at a calculated location. The graphics subsystem determines, by frequency, where the vector is placed along the X axis of the display. The color of the vector is also determined by this X axis location. The graphics subsystem determines, by amplitude and user-selected scaling options, the vertical axis, Y, to which the vector will be drawn. Time is referenced on the Z axis, thus defining a three-dimensional reference system.

## DISCUSSION

Changes in CEA occur quickly and may warn of impending disaster early enough to allow therapeutic intervention [10]. To detect events associated with ischemia or hypoxia, low-voltage activity must be monitored. For conditions such as seizures or responses to pain, rapid changes in activity must also be monitored. Frequency-amplitude analyses are well suited to these needs [11].

The algorithm provides a method for detecting rapid changes in CEA waveforms and is sensitive to small changes at frequencies from 0.5 Hz to 30 Hz. As with any algorithmic transformation, this approach has certain characteristics that bear upon its applicability to CEA processing. The technique can detect two frequency components simultaneously. Unlike Fourier analysis, which yields an estimate integrated over a time interval (usually 2 seconds or more), this algorithm presents amplitude and frequency on a wave-by-wave basis. Thus, events such as burst suppression can be easily detected. This wave-by-wave method allows detection of low-voltage, high-frequency CEA waveforms that can accompany brain hypoxia or ischemia.

## PSEUDO CODE DESCRIPTION OF THE APERIODIC ALGORITHM

The following description includes only the high-level pseudo code of the wave detection system; support procedures and ancillary functions of the front-end subsystem (i.e., continuous electrode impedance checking and artifact detection and rejection) have been omitted.

The Lifescan EEG monitor incorporates a dual-channel (left and right hemisphere) analog signal-processing front-end subsystem. Each channel consists of an independent set of filters, an analog-to-digital converter, and a microprocessor. The pseudo code describes the processing sequence of a single channel.

The algorithm implements a number of digital signal filters to perform the various signal processing tasks. The front-end subsystem has additional hardware band-pass filters to suppress frequencies below 0.3 Hz and above 120 Hz.

All computations are performed as signed integer arithmetic.

Items in the main procedure included for clarity but not further elaborated as pseudo code procedures are noted as "(not expanded)."

```
BEGIN main routine
  WHILE (1 = 1)
    Wait and service real-time
    interrupt
    60-Hz notch filter             (remove 60-Hz noise)
    Detect high-frequency ar-      (not expanded)
    tifacts
    30-Hz low-pass filter          (pass EEG below 30 Hz)
    Detect fast-wave subroutine
    10-Hz low-pass filter          (pass EEG below 10 Hz)
    Detect slow wave
    Detect multiple artifact       (not expanded)
    EEG data to graphics sub-      (not expanded)
    system
  ENDWHILE
                                   (loop forever, invoking
                                   subroutines)
END main routine;

BEGIN real-time interrupt ser-     (interrupts occur 960
vice routine                       times per second, in
                                   phase with AC power
                                   line)
  READ A-to-D converter            (acquire the digitized
  (ADC)                            EEG signal)
  ISSUE start pulse to ADC         (start the next ADC
                                   conversion)
END real-time interrupt service
routine

BEGIN 60-Hz filter subroutine
  IF k = 15                        (remove 60-Hz noise
                                   and DC offset from ac-
                                   quired EEG signal)
    k = 0
  ELSE
    k = k + 1                      (16-element array; each
                                   element is 1/16 of one
                                   cycle of 60 Hz)
  ENDIF
  60-Hz offset [k] = (60-Hz
  offset [k]* 256 + acquired
  ADC value) / 256
  Filtered voltage = acquired
  ADC value − 60-Hz offset [k]
END 60-Hz filter subroutine

BEGIN 30-Hz filter subroutine
  FOR i = 1 to 2                   (twice through the loop
                                   is equivalent to a hard-
                                   ware two-pole filter)
    IF k = 7
      k = 0
    ELSE
      k = k + 1
```

```
    ENDIF
    30-Hz smoothing array [k]         (two 8-point smooth-
    = input voltage                   ings have 3 dB cutoff at
                                      30 Hz)
    Output voltage = AVER-            (form the moving block
    AGE (30-Hz smoothing ar-          average)
    ray [k from 0 to 7])
  NEXT i;
END 30-Hz filter subroutine

BEGIN 10-Hz filter subroutine
  FOR i = 1 to 2;                     (twice through the loop
                                      is equivalent to a hard-
                                      ware two-pole filter)
    IF k = 23
      k = 0
    ELSE
      k = k + 1
    ENDIF
    10-Hz smoothing array [k]         (two 24-point smooth-
    = input voltage                   ings have 3 dB cutoff at
                                      9 Hz)
    Output voltage = AVER-            (form the moving block
    AGE (10-Hz smoothing ar-          average)
    ray [k from 0 to 23])
  NEXT i;
END 10-Hz filter subroutine

BEGIN fast-wave detection sub-        (find a valley)
routine
  IF a valley is detected from the
  filtered voltage
    IF a peak was previously de-      (found positive peak)
    tected before this valley
      IF a valley was previously      (valley-peak-valley im-
      detected before the peak        plies an EEG wave is
                                      detected)
        IF time between valleys       (8.0 Hz to 29.9 Hz)
        is greater than or equal
        to 33 ms AND less
        than 125 ms
          RESET all fast peak
          detection flags
          Frequency of fast
          wave = 1 / time be-
          tween valleys
          Amplitude = (height
          of first valley to peak
          + height of second
          valley to peak) / 2
        ENDIF;
      ENDIF;
    ENDIF;
  ENDIF;
END fast-wave detection subroutine

BEGIN slow-wave detection
subroutine
  IF the filtered voltage has         (detect positive peaks)
  crossed 0 V going positive
    IF the filtered voltage is less
    than the previous maximum
    reading
      Most positive peak =
      previous maximum read-
      ing
      SET most positive peak
      detected flags
    ELSE
      Previous maximum read-
      ing = filtered voltage
    ENDIF
  ELSE
    IF filtered voltage is greater    (detect negative valleys)
    than previous minimum
    reading
      Most negative peak =
      previous minimum read-
      ing
      Set found valley flags
    ELSE
      Previous minimum read-
      ing = filtered voltage
    ENDIF
  ENDIF
  IF found valley                     (if valley has been de-
                                      tected, start processing
                                      the wave detection using
                                      the same method as for
                                      fast waves)
    IF a positive peak was de-
    tected prior to this valley
```

```
IF a valley was detected        (a complete slow wave
prior to this positive peak     is detected: valley-peak-
                                valley)
  IF time between valleys
  is greater than or equal
  to 125 ms AND less
  than or equal to 2,000
  ms
    Reset all slow peak
    detection flags
    Frequency of slow
    wave = 1 / time be-
    tween valleys
    Amplitude = (height
    of first valley to posi-
    tive peak + height of
    second valley to posi-
    tive peak)/2
  ENDIF
ENDIF
ENDIF
ENDIF
END slow-wave detection routine
```

## GLOSSARY

APERIODIC Waveforms not characterized by consistent periods.

APERIODIC ANALYSIS METHOD A patented method of analysis, used in the Neurometrics Lifescan electroencephalographic monitor, that takes into account the peaks and valleys of the electroencephalographic signals.

ARTIFACTS Components of the electrical signals detected over the skull that are not generated by nervous system activity. Example: amplifier distortion caused by overvoltage (greater than 400 μV), by 60-Hz activity from the power line, by muscle movement, or by interference from other equipment.

CEREBRAL ELECTRICAL ACTIVITY (CEA) The electrical potential difference measured between two electrodes placed on the skull and resulting from the electrical activity of underlying nervous tissue.

ELECTROENCEPHALOGRAM (EEG) Term originally meaning the strip chart recording of CEREBRAL ELECTRICAL ACTIVITY but now often used in the medical literature to refer to the cerebral electrical activity itself.

EPOCH The time period over which the Fourier transform of the CEREBRAL ELECTRICAL ACTIVITY is calculated (typically 2 seconds).

FILTER A hardware device or software routine designed to pass signals of selected frequencies while rejecting others.

FAST FOURIER TRANSFORM (FFT) An efficient means of digitally computing the Fourier transform of a signal.

FOURIER ANALYSIS A technique for calculating the amplitude of a sinusoid. Any waveform can be represented as the sum of a set of sinusoidally varying waveforms of harmonically related frequencies. Fourier transformation of a time-varying waveform results in a representation that varies with frequency [12,13]. A true Fourier transform includes the relative phase of each component frequency. However, phase information is rarely provided in ELECTROENCEPHALOGRAM analysis.

MOVING BLOCK AVERAGING Averaging of data over a specified interval. Each data point is given the same weight in the average.

PHASE LOCKED The state whereby the analog-to-digital sampling rate is synchronous with the line frequency. Example: sampling 960 times per second would yield exactly 16 samples for each cycle of a 60-Hz signal.

RING BUFFER A buffer in which each new data point is stored in the next location. The layout is such that the next location ultimately becomes the first location.

STOCHASTIC Involving a randomly determined sequence of observations, each of which is considered as a sample of one element from a probability distribution. Stochastic variation implies randomness as opposed to a fixed rule or relation in passing from one observation to the next in order.

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