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A WAVE PATTERN ANALYSIS FOR EEG SIGNAL BASED UPON A SUCCESSIVE DIGITAL SMOOTHING PROCESS

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The electroencephalogram (EEG) is a signal representing variations in electrical potential between different points of the head. We are concerned in this paper with the analysis of a single channel of signal. Although the traditional analysis of EEG has been by visual observation of the signal written on recording chart, several types of computer analysis have recently been presented. The computer methods can be divided into two categories: those based upon harmonic analysis (autocorrelation, power spectrum, Fourier analysis) of the signal and those based upon pattern recognition.

In the method of harmonic analysis, it is assumed that the signal is composed of a number of waves of different amplitude and frequencies which are summed together. The many variations and applications of this method have been recently reviewed by Brazier.[1] The analysis usually takes one of two forms: an autocorrelation which reveals periodicities in the signal and the power spectral analysis which shows the amount of power in the signal at each frequency. Although each of these methods provides an excellent summary of the signal properties, neither provides a clear distinction between amplitude and frequency. Other characteristics of the signal such as symmetry and sequential properties are not covered in these analyses.

Several researchers have described pattern recognition methods for EEG analysis. A simple device was developed by Bickford[2] which would turn on an EEG chart recorder when a spike-and-wave discharge appeared (thus limiting the usage of the recorder to only those events of clinical interest). Computers have been programmed to "search for" specific patterns such as an alpha wave of specific frequency and amplitude (Farley,[3] Molnar et al.[4]). Brazier[1] has developed several methods of EEG analysis based upon the recognition of particular spike patterns.

In addition to these procedures for recognizing specific patterns, general "schemes" for pattern recognition have been described by Bonner.[5] These schemes have adaptive properties which are similar to those used in the classification of patterns by humans. In applying their methods to EEG, the signal is analyzed into "peaks and valleys" which are classified according to seven amplitude categories. (There apparently is no direct consideration of frequency.)

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Still another method of analysis involves aspects of both the harmonic analysis and pattern recognition. In Burch's "period analysis,"[6] the signal is categorized according to "periods" (or wave lengths) by a method of infinite peak-clipping or zero-crossings. A type of harmonic analysis is performed by considering in addition to the basic signal, the first and second derivatives of the signal, which provide information about higher frequencies which may be present.

Each of the systems described above provides information about certain aspects of the EEG signal. Harmonic analyses and "period analysis" provide information largely on frequency properties, and the pattern analyses have been concerned with special features (spikes, for example) or amplitude considerations. In the method discussed in this paper, a more nearly complete description of the signal is given. Categories of amplitude and frequency, and, in addition, symmetry are considered.

WAVE PATTERN ANALYSIS

We consider "digitized" EEG signal, that is, a series of positive integers which are proportional to the value of the signal voltage sampled at regular intervals (usually 100 to 300 samples per second). The process basic to the analysis is the identification of maxima (peaks) and minima (valleys) in the digitized signal. A maxima is identified by a series of three points, the middle of which is greater than the other two, while for a minima, the middle point must be less than the other two. (When several successive points have the same value, and these points are followed and preceded by points which are both of lesser or greater value, then a maxima or minima, respectively, is said to have occurred at the middle value.) A pair of successive maxima define the boundaries of a *valley wave,* and a pair of successive minima define a *peak wave* We are concerned with four properties of individual waves: *frequency, amplitude, symmetry,* and *complexity*. In addition, we may consider small groups or sequences of waves according to conditional probabilities or in terms of larger patterns.

Figure 1 illustrates the definitions of the various wave properties. Signal 1 shows the valley and peak waves. Note that the right hand minima defining the peak wave is the middle point of three equal values. For the peak wave, the *frequency* is the reciprocal of the duration D in seconds. The *amplitude* of this wave is the average of A and B, and the *symmetry* of the wave is the ratio of A to B (or B to A, whichever is larger). Similar definitions apply to the valley wave.

It is well known that in EEG signal, waves of different frequencies may be present simultaneously. Fast waves are superimposed on slow waves. Signal 2 of Figure 1 illustrates this characteristic of *complexity:* waves 4, 5 and 6 are superimposed on wave 3, and waves 2, 3 and 7 are superimposed on wave 1. If appropriate low pass electronic filters were applied prior to digitizing the signal, a subsequent analysis might yield only waves 2, 3 and 7 or if a low enough filter were used, only wave 1. We may define *simple waves* as those which can be identified without filtering, and *complex waves* (waves 1 and 3 in the illustration) as those which require filtering for identification.

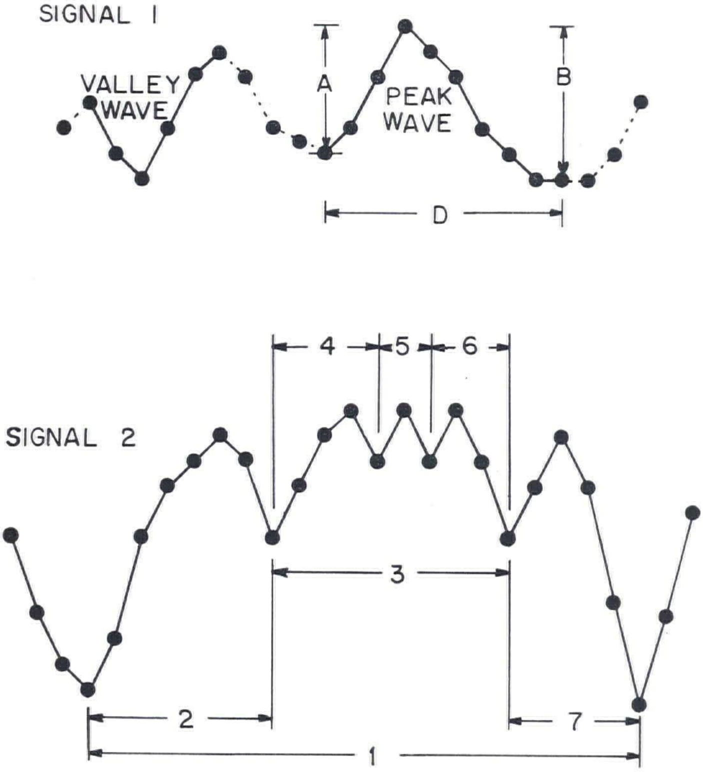

Figure 1

Illustrations of wave properties. Signal 1 shows a *valley* and *peak wave* and is used to define *frequency* (1/D, where D is in sec), *amplitude* (average of A and B), and symmetry (ratio of A to B). Signal 2 illustrates the property of complexity. *Waves* 4, 5, and 6 are superimposed on wave 3, and waves 2, 3, and 7 are superimposed on wave 1. Waves 1 and 3 are *complex*, the others are simple.

A complete specification of the complexity of a particular wave would require a knowledge of all waves (revealed by all possible filters) which overlap in time with the given wave.

In the specific analyses described below, a process of *digital smoothing* by computer is performed instead of electronic filtering to reveal this property of complexity. In the first of several stages of smoothing, all waves are identified and those which have a frequency greater than 50 cps are replaced by digits of constant value so that they will not affect the identification of maxima and minima. (The details of the smoothing process are important and are described below.) The new maxima and minima are determined and the wave properties are computed. The frequencies, amplitudes, symmetries and sequences of waves determined after 50-cps smoothing constitute one set of data. In a similar manner, the smoothed signal is now resmoothed so that any waves with frequencies greater than 25 cps are replaced by constant values. The wave properties are again determined and a set of data for 25-cps smoothing is obtained. Similary, sets of data for 15 and 8 cps (or other criteria) smoothing are determined.

The details of the smoothing process are important and many other methods were tested before the present one was chosen. The most obvious method might be some type of averaging process. Such methods are not satisfactory because they provide a very unpredictable frequency cut-off and may lead to the generation of frequencies not present in the signal due to phase relationships (called aliasing in power spectrum theory). Another problem is that a high amplitude, short duration spike may be counted, after averaging, as a low amplitude, slow wave. Another possibility is simply to use successive stages of electronic filtering. For many applications this may be adequate, but it is probably not as convenient, and some of the problems associated with averaging also apply to electronic filtering. In the smoothing process describe below, a peak or valley wave is replaced by digits of constant value if it is of greater frequency than a specified cut-off. Before the present method was chosen, several variations were rejected on logical grounds (often after testing revealed weaknesses): smoothing on the basis of criteria for half waves, use of a replacement process in which the constant value runs from minima to minima or maxima to maxima (see below), and smoothing of only peak waves.

The procedure used for digital smoothing is as follows. If a peak or valley wave is of greater frequency value than the specified cut-off, it is smoothed, but if it is of smaller frequency, it remains in its original form. As long as the previous wave has not been smoothed, we consider every (overlapping) peak and valley wave. But if a peak wave is smoothed, the next (adjacent) peak wave (disregarding the overlapping valley wave) is considered. Correspondingly, if a valley wave is smoothed, the adjacent valley wave is next considered.

By smoothing, we mean a replacement of digits according to one of the four procedures illustrated in Figure 2A. If a peak wave is smoothed, we replace the digits shown by values equal to the greater of the two minima bounding the wave. Note that the replacement begins at the greater minima and proceeds across the wave until the wave boundary is reached. Valley waves are smoothed by a replacement according to the smaller of the two maxima. It is important to note that if the initial smoothing criterion is chosen at too low a frequency, all waves above the criterion frequency may not be smoothed. Smoothing must either be repeated several times at low frequency or be done using a series of successively lower stages. To clarify this point, let us say that we are initially smoothing at 20 cps. Two 70-cps waves may be smoothed to form a 35-cps wave which is above the cut-off. If the smoothing process is repeated, the 35-cps wave will disappear.

Figure 2B shows the smoothing process applied to a hypothetical signal. Six maxima and seven minima are shown (by arrows) for the unsmoothed signal but for the smoothed signal there are two maxima and three minima.

A feature of the pattern analysis is the ease at which certain types of non-EEG signal can be recognized and rejected. Muscle potentials appear in the form of high amplitude, high frequency waves. Appropriate amplitude and frequency criteria can

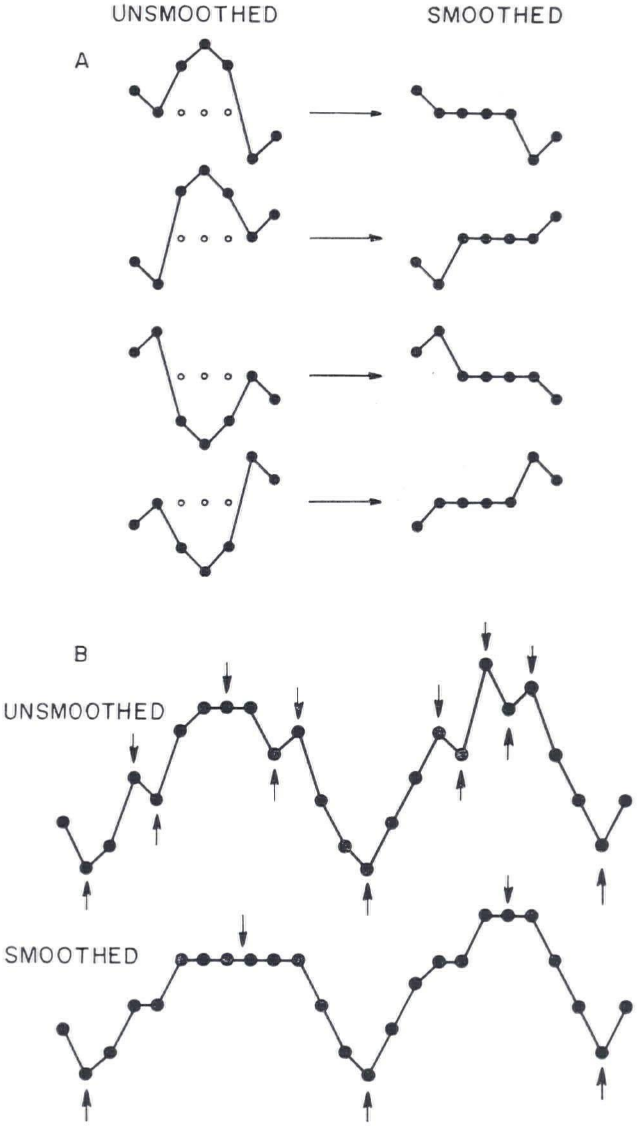

Figure 2

Illustrations of the digital smoothing process. A. The smoothing process applied to the four basic types of waves. The small unfilled circles show the resulting values after smoothing. B. An example of the smoothing process applied to a complex signal (the upper curve). The lower curve shows the resulting smoothed signal. The arrows designate the maxima and minima.

be established and if a given number of such waves are found within an interval of time, then that interval can be disregarded. Another type of signal easily recognized as non-EEG is a number of consecutive digits which are of extremely high or low value. Such signals are characteristic of recordings taken with loose electrodes. Illustrations of artifact rejection are presented below.

AN APPLICATION

As an initial test of the pattern analysis program, a period of human sleep was analyzed. Dement and Kleitman[7] have described four stages of sleep according to EEG pattern and have found cyclic variations in depth of sleep. Since the patterns of EEG associated with sleep are well known, it was decided that this would be a good example for bringing out the major features of the analysis. The signal analyzed was recorded between left central and left occipital electrodes (see Maulsby[8] for more information on the recording conditions).

The application of a relatively simple pattern analysis will be described first. The details of the computer program used are as follows. Epochs of 10.0 sec were regularly sampled each minute. For each epoch, all valley and peak waves were determined after each of four smoothing processes. Frequencies greater than 50, 25, 15 and 8 cps were successively smoothed out of the analyzed signal. For each smoothing cut-off, valley and peak waves were classified according to frequency band and amplitude. The frequency bands were delta (1 to 3.49 cps), theta (3.50 to 7.99 cps), alpha (8.00 to 14.99 cps), beta-1 (15.00 to 24.99 cps), beta-2 (25.00 to 34.99 cps) and beta-3 (35.00 to 49.99 cps). Amplitude was considered in only two categories: larger than a certain criterion or smaller (and not counted). The criterion was proportional to the wave duration and was approximately 10 to 12 units for frequencies from 50 to 16 cps and 50 to 80 units for frequencies from 15 to 1 cps. The units come from an arbitrary scale of 0 to 510 which was used for the digitization of the signal. One hundred units, the amplitude of a large alpha wave, was about 50 microvolts.

As described above, criteria were used for the rejection of epochs of EEG signal which contained artifacts. For rejection purposes, every 10-sec epoch was divided into 2-sec intervals. Appropriate criteria depend, of course, on the method of digitization and upon a knowledge of the characteristics of EEG and the particular method of recording. The criteria used for muscle spike rejection was 12 or more spikes within the 2-sec interval. A spike was defined as a minima to maxima rise of at least 45 units within 16 millisec. The extreme value criteria for rejection of a 2-sec interval was a continuous period of at least 0.5 sec in which the value of the digitized signal was either greater than 337 or less than 174 units. These criteria were developed by trial and error with the advice of an electroencelphalographer[9] and were verified by comparison with a standard reference.[10] Examples of the artifact rejection are given in Figure 3.

Figure 4 shows the percentage of time that the signal was in each of four frequency bands (recorded after different smoothing cut-offs): beta-1 at 50-cps smoothing cut-off, alpha at 25 cps, theta at 15 cps, and delta at 8 cps. A much more nearly complete analysis is described below. The data represent averages for 5-minute intervals (five 10-sec samples, one sample per minute) and the hour and minute for the beginning of each interval is shown. For each interval, a number is shown which represents, approximately, the average stage of sleep (as interpreted by Maulsby[8]) during that interval. It is apparent that the delta (at 8 cps) and theta (at 15 cps) bands

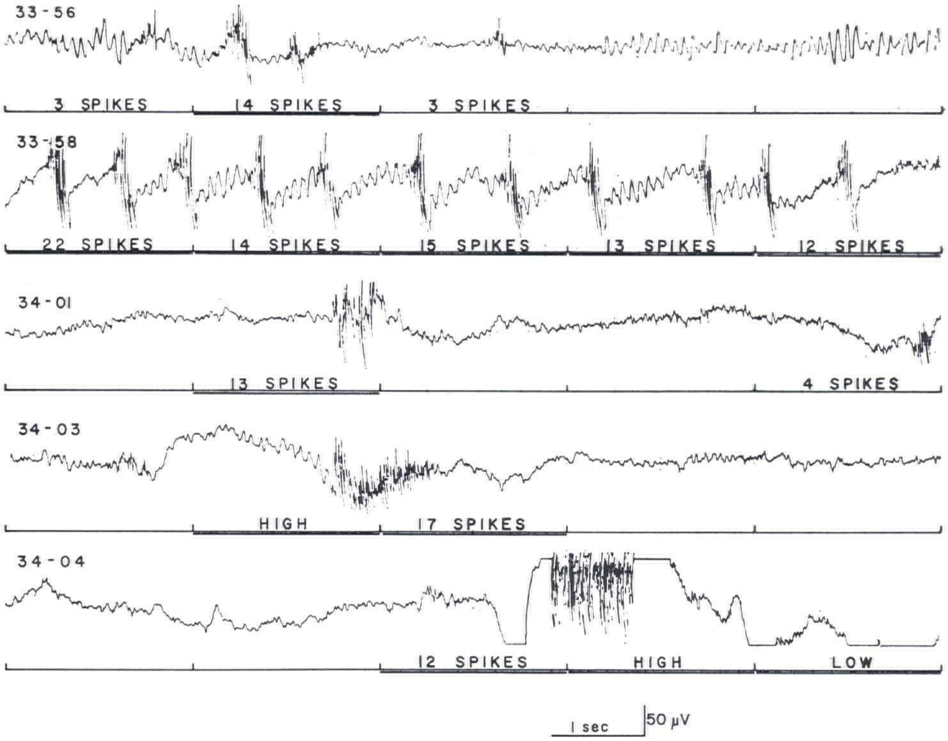

Figure 3

Examples of artifact rejection. Five 10-sec epochs of signal are shown, and the hour and minute for each epoch is given in the upper left hand corner. For each 2-sec interval, the number of "muscle spikes" (defined as a maxima to minima rise of at least 45 units within 16 ms) is shown if greater than zero. If 12 or more spikes were found within a 2-sec interval, the interval was not accepted (double line) for further analysis. The words "high" and "low" designate those intervals rejected by the "extreme value criterion" (a continuous period of at least 0.5 sec in which the value of the digitized signal was either greater than 337 or less than 174 units). Note: an interval rejected by the extreme value criterion was not tested for muscle spikes.

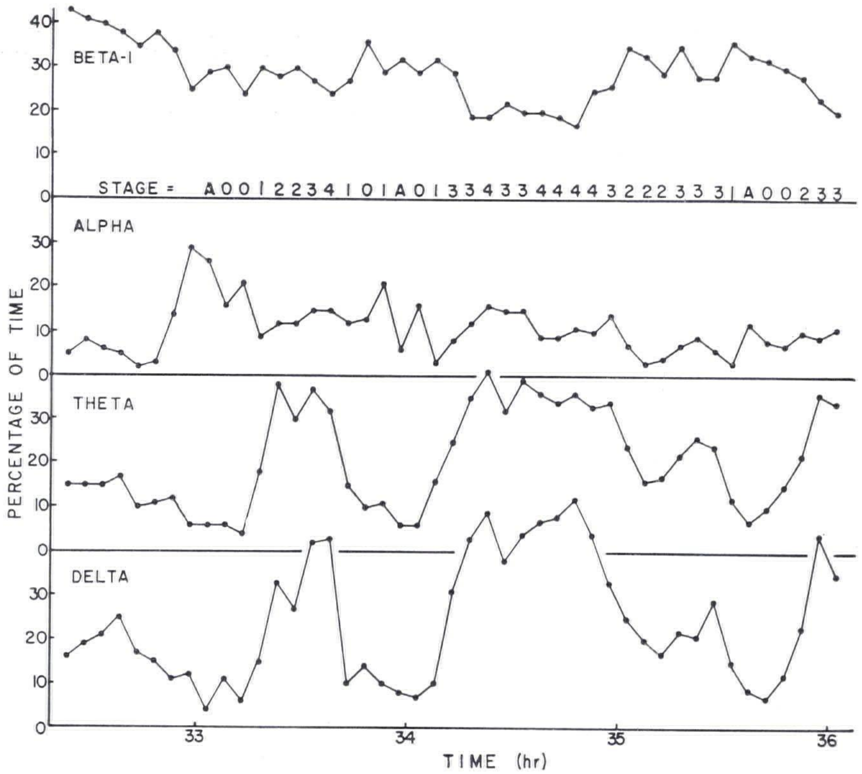

Figure 4

Percentage of time that the signal was in each of four frequency bands: beta-1 at 50-cps smoothing cut-off, alpha at 25 cps, theta at 15 cps, and delta at 8 cps. The data represent means for 5-minute intervals beginning at 32 hr, 23 min. Near the top of the figure, a row of numbers designates the approximate stages of sleep as interpreted by Maulsby.[8] Numbers 1 to 4 represent the stages from light to deep sleep, "A" designates the eyes-open state, and "O" is the resting, eyes-closed state (alpha rhythm). Note the close correspondence between the delta and theta bands, and the stages of sleep.

are quite closely related to the depth of sleep. The alpha band (at 25 cps) shows a peak in the drowsy period just before the onset of sleep. Some small increases in the alpha frequency range occur at the peak of delta activity. These represent faster activity superimposed on the slow sleep waves. The beta-1 band shows an almost perfect inverse relation with the depth of sleep. In the more detailed program which will now be discussed, some of the relationships discussed above may be clarified.

The more elaborate program was applied to the same 10-sec epochs described above. The same smoothing cut-offs were used but valley and peak waves were classified into more categories of frequency and amplitude and additionally, symmetry. The frequency bands were: 0 to .99 cps, 1.00 to 2.99 cps, 3.00 to 4.99 cps, 5.00 to 6.99 cps, . . . 15.00 to 16.99 cps, greater than 17.00 cps. The amplitude categories were: 1 to 19, 20 to 79 and 80 units or greater. Symmetry was defined above with reference to Figure 1A. The measure of symmetry used was either the ratio of A to B or B to A, whichever was greater than one. The categories for symmetry were: 1.000 to 1.200 (symmetric), 1.201 to 3.000 (asymmetric), greater than 3.000 (very asymmetric).

Five 10-sec epochs of EEG, each representing a stage of sleep (as interpreted by Maulsby[8] and verified by the author) were compared. These five samples, shown in Figure 5, were chosen because they are relatively homogeneous throughout the 10-sec period, they contained no artifacts by the criteria described above, and because they clearly fit into their respective categories.

Since there are so many categories to consider and because it is desirable to see all the categories together, it was decided to represent the number of waves falling into each category by a circle, the diameter of which is proportional to the number. In Figure 6, grouping is by sets of nine categories (3 by 3 arrays) in which amplitude increases from left to right and asymmetry increases from top to bottom. Thus, the upper right corner of a 3 by 3 array represents an almost symmetrical wave of high amplitude. The lower left hand corner would be a highly asymmetrical wave of low amplitude. It is apparent from the figure that most of the activity falls in the middle amplitude, medium asymmetry category (all circles except the middle one are filled, so as to emphasize deviations from the middle ranges).

Before examining Figure 6, it is well to keep several ideas in mind. First of all, since smoothing is on the basis of frequency, certain bands cannot have activity in them. For example, 8-cps smoothing removes all alpha from the signal. Another point is that at high smoothing cut-offs, only simple waves (those without higher frequencies superimposed on them) are identified. It was found, for example, that all delta activity (1-3 cps) is complex since the 50 and 25 cps smoothing categories are all zero. (The 50-cps smoothing category is not shown since it is very similar to the 25-cps category.) The third point is that for slow waves, the lower amplitude categories have little meaning in terms of an ordinary visual analysis of EEG. When a signal is progressively smoothed at lower and lower frequencies, slow waves will appear even if they only represent some kind of statistical fluctuation or possibly "spindling." If we consider

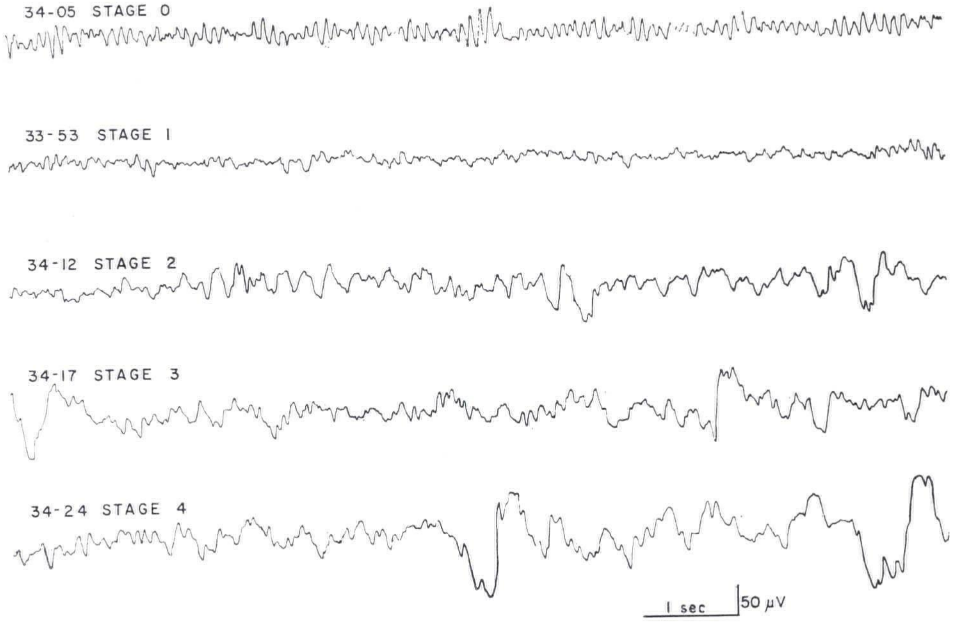

Figure 5

Five 10-sec epochs of EEG, each representing a stage of sleep (hour and minute are shown at the left). These epochs were used for the analysis illustrated by Figure 6.

only higher amplitude categories for the slower waves (at low frequency, smoothing cut-offs), however, these statistical fluctuations disappear. (It should be noted that although we do not readily "see" these fluctuations, they are still valid properties of the signal and may turn out to be of interest.) The last point is that it is well to remember in examining this figure that a given number of waves in the low frequency categories represent a greater percentage (time-wise) of the signal than an equal number of high frequency waves.

Let us first consider the obvious differences between the EEG epochs characterizing the various stages of sleep, disregarding symmetry for the moment. Stage 0 is on the borderline of waking and sleeping (resting with eyes closed) and is characterized by a strong alpha rhythm (around 8 to 13 cps). The figure shows large amounts of 9 to 11 and 11 to 13 cps activity at all smoothing cut-offs. Stage 1 of sleep is characterized by its low voltage activity with a complete lack of spindling. The figure for stage 1 shows that the activity is spread through the theta, alpha and beta bands with a complete absence of high amplitude waves (no circles in the right hand columns of the 3 by 3 arrays). The highest numbers of frequencies greater than 17 cps appear in this stage. Most characteristic of stage 2 sleep is moderately high voltage theta activity. We see the reappearance of high amplitude activity in the figure under the 3 to 5 cps (low theta) category. Stages 3 and 4 of sleep are characterized by increasing amounts of high voltage delta waves. The figure shows increasing amounts of high

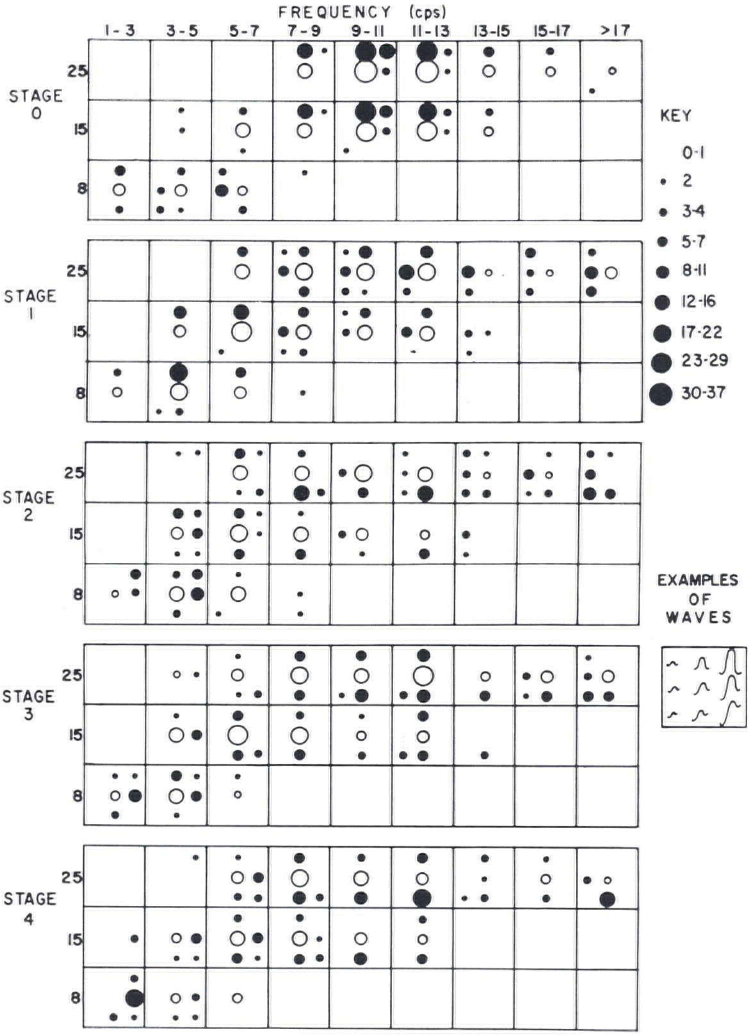

Figure 6

The wave pattern categories for the five 10-sec epochs shown in Figure 5. The number of waves in each category is represented by a circle (see key at right). The nine columns are for the frequency bands, and the rows are for each of three smoothing cut-offs (25, 15, and 8 cps). Each small 3 by 3 array represents categories of increasing amplitude from left to right, and increasing asymmetry from top to bottom. All circles except the center one are filled to emphasize deviations from the middle values. Examples of waves (only peak waves with one type of asymmetry are shown) found in these categories are given at the right. This small diagram may serve as a rough guide for interpreting the figure. (See text for exact definitions of categories.)

amplitude activity in the 1 to 3 cps range. In addition, there are relatively large values in the 13 to 17 cps ranges which may be related to the sigma (14 cps) activity usually associated with stage 3.

After this brief examination of the figure, it may have been noticed that for some bands there is a relatively constant number of waves for all stages. Most constant, perhaps, is the 5 to 7 cps band for 15-cps smoothing. This band only shows a significant decrease for stage 0. Other bands in the middle frequency ranges and at middle smoothing cutoffs tend to remain fairly constant. This constancy probably reflects the "random" character of EEG signal. In most cases, there will always be a certain number of waves in the middle categories.

The top rows of the 3 by 3 arrays indicate highly symmetrical waves and the bottom rows, highly asymmetrical waves. As might be expected, the stage 0, alpha rhythm, shows the greatest number of symmetrical waves, and high amplitude alpha is almost entirely symmetrical. In stages 1 and 2, low frequency theta waves (3 to 5 cps) seem to be relatively symmetrical. More striking, perhaps, is the large amount of asymmetrical waves which occasionally appear, such as in the alpha range for stages 2 and 4. Asymmetry was particularly high for the 11 to 13 cps band at the 50-cps smoothing cut-off (not shown in the figure). Apparently there is a large amount of this asymmetrical alpha activity superimposed on the slower delta and theta waves.

The complexity of the EEG signal may be determined by examining changes in the distributions of waves after successive smoothings. Let us first consider stage 4 because it is apparent even from a casual observation of an EEG chart that the slow delta waves have many higher frequencies superimposed on them. At 50-cps smoothing (not shown in the figure), there are almost no waves below 7 cps, but large amounts between 7 and 13 cps, and above 17 cps. At 25-cps smoothing, almost all of the activity above 17 cps has disappeared, and waves around 8 cps are appearing. This shift to lower frequencies continues until at 8 cps, high amplitude 1 to 3 cps waves predominate. It may also be noticed that within the 9 to 11 cps column the number of waves decreases from the 25 to 15 cps cut-off even though the waves are slower than the criterion frequency. An example will make clear how this can occur.

Consider two adjacent "peak waves," one 10 cps and one 20 cps, with the middle minima much higher than the two outer minima. With a 15-cps criterion, the 20-cps wave is smoothed, but the 10-cps wave is not smoothed. However, when the maxima and minima are redetermined, the 10-cps wave also disappears and we are left with one 6.7-cps wave, the combinations of the 10 and 20 cps waves.

Compare the smoothing process for stage 4 with that for stage 0. With a fairly homogeneous pattern such as the alpha rhythm, the 9 to 13 cps activity is mostly retained even down to 15-cps smoothing. However, for stage 0 at 8 cps smoothing, some low amplitude delta waves are recorded. These are due to slow shifts in the overall alpha pattern and to spindling. These "alpha-associated" delta waves are easily distinguished from stage-4-sleep deltas by their low amplitude.

DISCUSSION

Wave pattern analysis provides a straightforward, but detailed, categorization of EEG signal according to the familiar concepts of frequency, amplitude, and symmetry. It provides an analysis in which the treatment of each wave can be specified exactly and in simple terms. The computer time for the method is not excessive, particularly when the signal has been electronically filtered.

The major features of the analysis were brought out in an application to human sleep records. Perhaps the most unique feature of the method is the way in which complex waves, those slow waves which have fast waves superimposed on them, can be analyzed. A process of successive digital smoothing according to frequency criteria is used. By comparing the first stages of this process to the last, the complexity of the signal can be determined. Another feature is the measure of symmetry which was defined in Figure 1A. The analysis showed, for example, that the familiar alpha rhythm is quite symmetrical, and that waves in the 9 to 13 cps range which are superimposed on delta waves, are quite asymmetrical. Criteria for examining the signal and rejecting artifacts was found quite valuable in making the analysis more rigorous, and in speeding the treatment of large quantities of data.

One of the most difficult questions for any type of EEG analysis is how to summarize the information after the basic data reduction is made. Most of the specific problems fall into one of three cases. The problem may be to: search for a particular pattern; compare several epochs of EEG which correspond to different treatments; or to make a general analysis of EEG taken over a long period of time. For the first case, we may simply state when the pattern has occurred, and for the second case, a chart such as shown in Figure 6 may be prepared. One solution for the third case is to greatly reduce the number of categories and present data for certain bands such as in Figure 4. Except for certain special purposes, however, too much information would be lost by this solution.

Perhaps the best approach is to present a complete categorization of the wave patterns for the total time period, and then to show those times at which particular categories are greatly different from the mean. This difference might be in terms of a certain number of standard deviations or a certain percentage of the mean.

One of the most useful features of the wave pattern analysis is the ease with which the method may be modified according to specific needs. An example already presented is the "muscle spike criterion" for data rejection. The muscle spike is only one of many possible special patterns which could be recognized. Additional categories could be made up for any type of spike simply by specifying amplitude and frequency (or rise time) criteria. In a similar way, a slow wave of a particular duration and amplitude range could be "searched" for. It might be desirable to make categories for certain pairs of waves, such as a spike followed by a delta wave, or a pair of symmetrical slow waves.

The treatment of the properties of frequency, amplitude, symmetry and complexity by wave pattern analysis has been discussed. In addition, methods have been suggested for studying sequential properties and special features of the EEG signal. The wave pattern analysis may now be compared with other methods of computer analysis for EEG.

Consider first the property of frequency. Previous pattern analyses have either provided no information on frequency or have considered only particular frequencies.[3,4] Power spectrum and autocorrelation analysis provide excellent summaries of frequency properties of the signal, but the resulting values depend on both the number of waves at a particular frequency and the amplitude of those waves. Wave pattern analysis separates out these factors and provides amplitude categories for each frequency range. Period analysis (Burch[6]) summarizes frequency (but not amplitude) properties of slower waves ("major periods") by a baseline crossing method applied to the unmodified signal, and the frequencies for superimposed, faster waves by baseline crossings applied to the first and second derivatives of the signal (intermediate and minor periods). The results for the faster waves are similar to those obtained by the wave pattern analysis applied to unsmoothed signal, but for the slower waves, the baseline crossing method is not entirely satisfactory. The basic problem is that for a complex signal such as EEG, there is no unique choice for the baseline. Depending upon the moment to moment relationship of the baseline to the signal, any combination of small or large periods may be counted.

The treatment of the remaining signal properties by other methods may be quickly summarized. Complexity, which is studied in wave pattern analysis by the method of successive digital smoothing is not considered in other methods, with the possible exception of period analysis. Some difficulties with the treatment of slower waves (major periods), however, have already been discussed. Of the other methods discussed, only Bonner[5] considered amplitude categories, but no other properties of the signal are mentioned. The property of symmetry as defined by the author is not included in the other methods.

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