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Intraoperative EEG Patterns: Implications for EEG Monitoring

Warren J. Levy, M.D.*

Univariate descriptors such as the mean frequency and spectral edge frequency have been proposed for intraoperative representation of the EEG. Such univariate descriptors of the EEG are accurate only when the EEG behaves as a unimodal distribution of frequencies that change slowly with time. EEGs were recorded from 64 patients undergoing anesthetic inductions and 30 patients undergoing cardiopulmonary bypass to determine the characteristics of the observed distribution of frequencies. Multimodal EEG activity was observed in 64% of these cases, including 83% of those patients undergoing cardiopulmonary bypass. The differences between the two peaks averaged 7.6 Hz, and the average ratio of the power of the peaks to the intervening valley was 2.5:1 and 1.9:1. Calculations of mean frequency and spectral edge frequency failed to adequately reflect the complexity of the EEG in these cases. Burst-suppression activity was observed in 26% of cases during cardiopulmonary bypass, and averaging over time destroyed the characteristic pattern. Thus, univariate descriptors of the EEG appear inadequate to describe the behavior of EEG during anesthesia in a large percentage of cases.

(Key words: Brain: electroencephalography. Monitoring: electroencephalography.)

DURING THE PAST FEW YEARS, numerous methods of automated EEG processing have been suggested as appropriate for intraoperative monitoring of the EEG. Simple filter processing[1] (CFM), averaging,[2] waveform analysis,[3] and power spectrum analysis[4] all have been proposed as means of quantifying the EEG. When a complex analysis technique such as power spectrum analysis has been used, univariate descriptors such as the spectral edge frequency,[5] median power frequency,[6] or peak power frequency[7] have been proposed to simplify further this processing technique. There is an inherent appeal to such data reduction, and considerable simplicity may be achieved by reducing the EEG to a single number, even though the physiologic significance of the number has not been demonstrated. In such situations, the EEG must exhibit certain prescribed statistical behavior or the univariate descriptor cannot be considered to adequately describe the distribution. Specifically, the mean is a useful approximation of a distribution provided that the distribution is unimodal (has one peak) and is not excessively skewed. The spectral edge frequency is a one-sided measure of 95% range and as such would be expected to be relatively insensitive to low-frequency changes in a broad or bimodal distribution. Because the validity of statistical measures may be assessed from a knowledge of the distribution from which they were calculated, we examined the distribution of intraoperative EEG activity using short-epoch power spectrum analysis to see if the distributions of EEG power spectra would be described adequately by univariate descriptors.

Methods

EEG recordings were made in 64 patients undergoing anesthetic inductions, 30 of whom underwent cardiopulmonary bypass. These studies were approved by the Committee on Studies in Human Beings of the University of Pennsylvania, and appropriate consent was obtained. Electrode placement varied from case to case depending on clinical or research requirements. In all cases a common reference electrode montage was used. Either bilateral frontal and central (F_{p1}, F_{p2}, C_3, C_4) or right parasaggital (F_{p2}, C_4, T_4, P_4) leads were recorded to the right ear (A_2) using the left ear (A_1) as ground. The bandwidth of recording was 4–45 Hz (3 db points). The high-frequency filtration prevented digitization artifact (aliasing), while the low-frequency filtration reduced motion artifact during the induction. Premedication varied according to clinical requirements, most frequently being either morphine (0.1 mg/kg) and scopolamine (0.005 mg/kg) or no premedication at all. Diazepam, 5–10 mg, was used occasionally in addition to the morphine and scopolamine. Anesthetic inductions were performed with halothane, isoflurane, or enflurane in oxygen or nitrous oxide/oxygen mixtures, depending on requirements. Thiopental, fentanyl, or alfentanil also were utilized as induction agents. A total of 50 h of EEG recordings were processed.

Power spectrum analysis of the EEG was performed by on-line microcomputer using 256 samples for each channel during each 2-s epoch. The spectra were generated for frequencies between ½ and 48 Hz, with a resolution of ½ Hz. Power spectra were displayed using the density-modulated display format (DSA)[8] because of the ease of interpreting this display intraoperatively, and digitized spectra were saved for subsequent analysis. Average frequencies within epochs were calculated after weighting each component frequency by the calculated power at that frequency. Average spectra were obtained by averaging identical frequencies over several epochs. Power spectra were analyzed for the presence of multiple modes by inspection, because no standard statistical tests are available to assess the statistical significance of multimodality.[9] Because of the scaling of the DSA, bimodal distributions could be identified only if the nadir between modes was less than 70% of the lesser amplitude peak. Spectral edge frequencies were calculated as the frequency

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* Assistant Professor of Anesthesia.

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Address reprint requests to Dr. Levy.

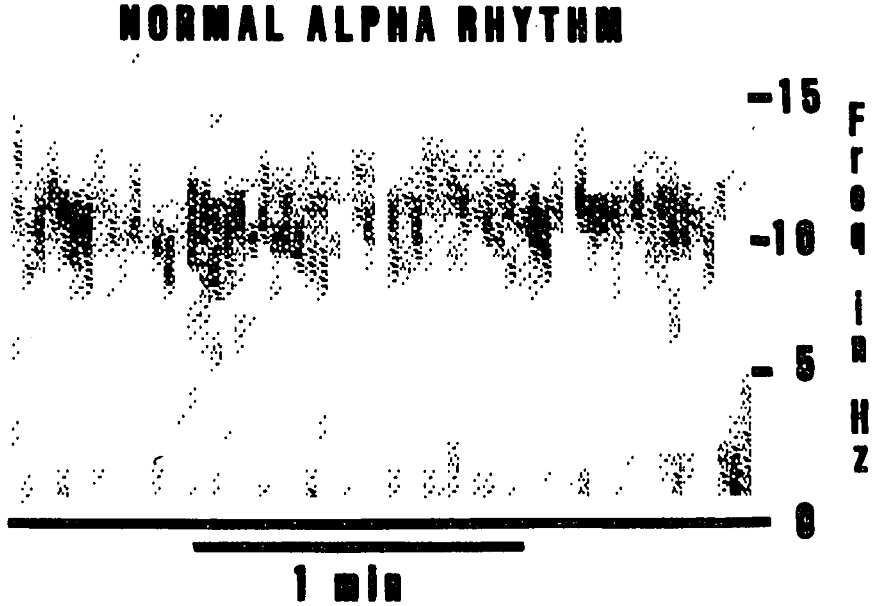

FIG. 1. Normal alpha rhythm. This DSA of a normal alpha rhythm demonstrates the narrow range of frequencies typically seen in such an EEG. Except for low-frequency artifact, essentially all activity is found between 8 and 12 Hz.

below which 95% of the total power in the spectrum was concentrated.[10]

Results

Bimodal patterns of EEG activity were observed in 63% of the cases studied. The incidence was highest during cardiopulmonary bypass, when 83% (25 of 30) of these patients demonstrated bimodal recordings; however, 37% (11 of 30) of these patients demonstrated bimodal recordings during surgery prior to bypass, when stable anesthetic conditions were present. Anesthetic agents in these patients included halothane (five cases), fentanyl (two cases), and isoflurane (three cases). In the 34 patients studied only during anesthetic induction, 42% (14 of 34) showed bimodal patterns of power spectral activity. On the average, the low-frequency peak appeared at 4 Hz (range 1–12 Hz), while the high-frequency peak occurred at 11.6 Hz (range 5–20 Hz). The difference in EEG amplitude between these peaks and the intervening valley also was substantial. The power of the lesser amplitude peak was 1.9 times the power of the nadir, while the power of the higher amplitude peak was 2.5 times that of the nadir. Burst-suppression activity during hypothermia was observed in 27% (8 of 30) patients studied during cardiopulmonary bypass.

Discussion

The EEG recorded in the normal awake resting adult contains most of its activity in a very narrow band of frequencies, the alpha band (fig. 1). Such a discrete band of activity can be easily and accurately represented by a single descriptor—most commonly the mean frequency. In such a distribution, the peak power frequency (the mode), the mean and the spectral edge frequencies all will behave in similar fashion because the distribution of frequencies is unimodal and very limited. Our results suggest that the EEG during anesthesia often is composed of several bands of frequencies, and univariate descriptors may not adequately describe the behavior of a complex EEG.

Previous work by Bart *et al.*[11] and Findeiss *et al.*[12] demonstrated the diffuse nature of the EEG power spectra that occur during anesthesia, but they did not extrapolate their findings to univariate descriptors. Because the mean and variance are sufficient to completely describe the normal (or Gaussian) distribution, the mean is the most frequently used univariate descriptor of a population. Unfortunately, its descriptive properties (indicating the region where most of the distribution lies) fail for non-Gaussian distributions such as bimodal power spectra. Figure 2 shows a graphic example of the misrepresentation of EEG changes when the average frequency is computed from a bimodal distribution. The development of a new low-frequency band reduces the average frequency to such an extent that the average occurs at a frequency at which there is actually very little EEG activity.

The spectral edge frequency also has been offered as a single variable descriptor of the EEG power spectrum, particularly during cerebral ischemia.[13] While it may be of value for this purpose, it generally does not reflect the bimodal EEG. Figure 3 shows a patient who responded to intubation (under ethrane/oxygen anesthesia) by eliminating almost all low-frequency activity, reducing the amplitude, and spreading the frequency distribution of

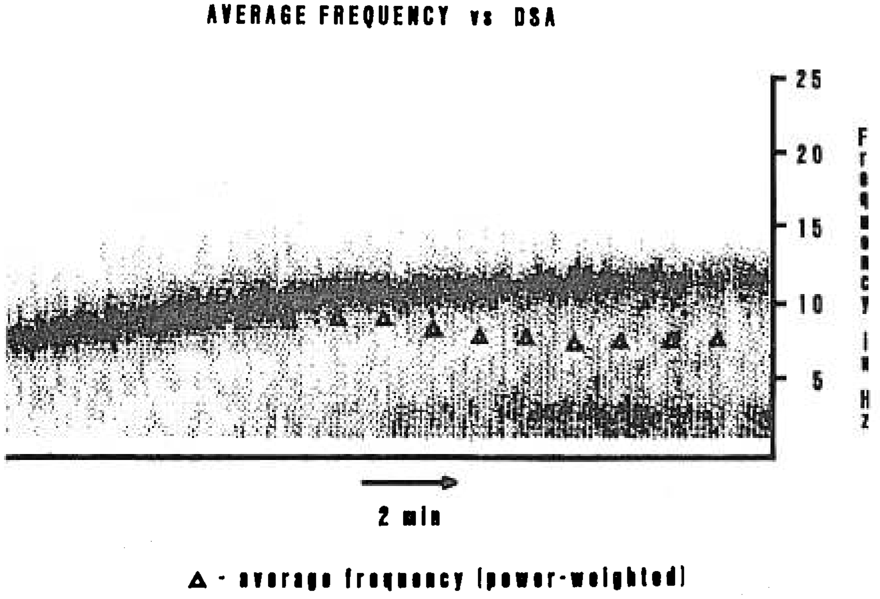

FIG. 2. A comparison of the DSA and power-weighted average frequency. During this 15-min period of rewarming, the distribution of the power spectrum changed dramatically. The upper band increased in frequency, while a new low-frequency band appeared. The power-weighted average (triangles), while mathematically correct, was not representative of the EEG behavior.

high-frequency activity. At A, a spectral edge frequency of about 15 Hz represented a bimodal EEG with a prominent lower band. Following intubation (B), the same spectral edge frequency represented a unimodal high-frequency EEG. Although the frequency of such misrepresentation of the EEG by the spectral edge frequency could not be determined in this study, such distortion would be expected when using a measure of range as indicative of an entire distribution.

The peak power frequency, while statistically a more valid descriptor of a bimodal distribution, is also potentially very misleading as a univariate descriptor of the EEG. This is exemplified in figure 4*A*, in which the presence of low-amplitude high-frequency activity implies a nonhypoxic etiology for the observed changes. In figure 4*B*, this activity is absent, and the spectral changes suggest a hypoxic etiology. The peak power frequency changes similarly in both patients and therefore does not provide

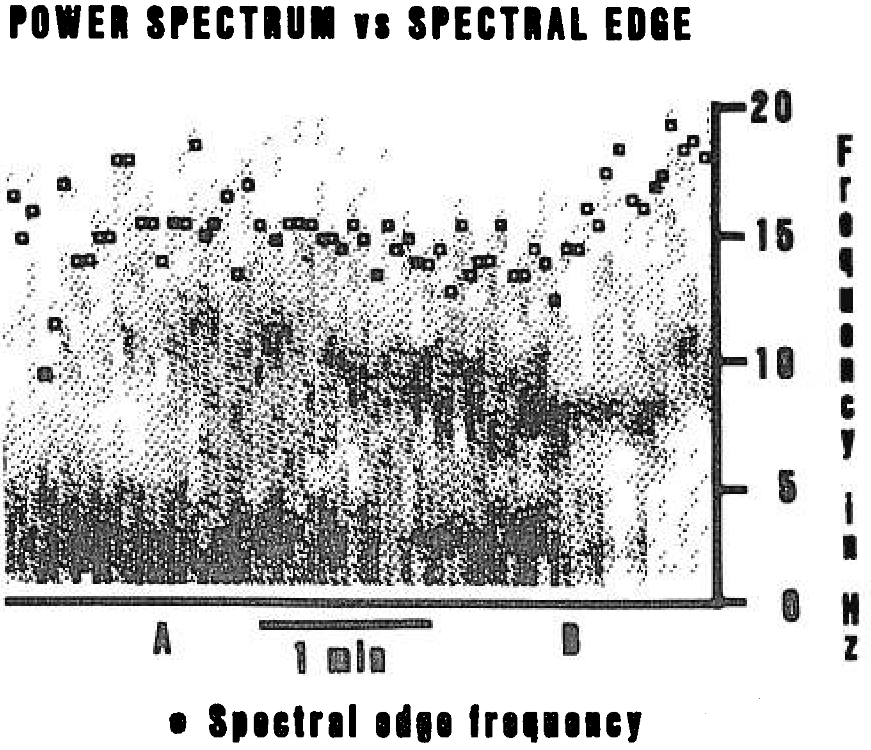

FIG. 3. A comparison of spectral edge frequency and DSA. This DSA was obtained during the induction of anesthesia with enflurane and oxygen in an unpremedicated patient. The entire sequence followed loss of consciousness and neuromuscular blockade with succinylcholine. A low-frequency band slowly decreases in amplitude until intubation (*B*) when it abruptly terminates. A higher-frequency band gradually decreases in frequency and increases in amplitude, while the spectral edge frequency stays rather constant. Furthermore, at (*A*) the spectral edge frequency represents primarily low-frequency activity, while after (*B*), the same numeric value represents primarily a high-frequency power spectrum.

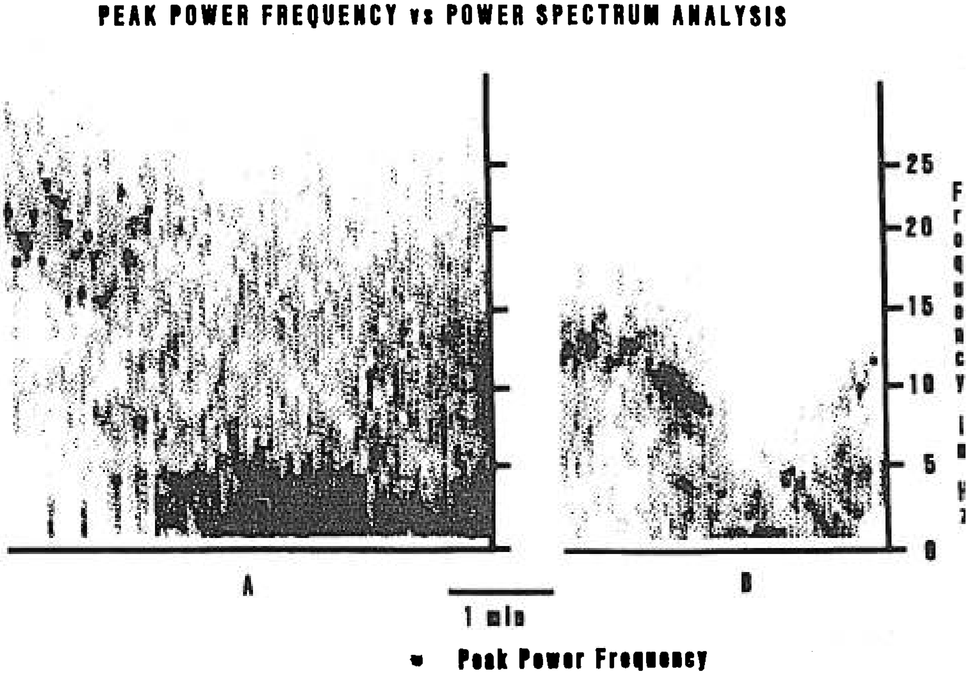

FIG. 4. A comparison of peak power frequency and DSA. Panel *A* was recorded during anesthetic induction with enflurane, Panel *B* during halothane anesthesia with cardiopulmonary bypass. Both panels show abrupt reduction of the initial peak power frequency. In *A*, the change is produced by deepening anesthesia, and small amounts of high-frequency activity in the DSA show that the change is benign. In *B*, produced by acutely reducing extracorporeal perfusion, the total absence of high-frequency activity suggests hypoxic etiology. In this case, the clinical significance of the EEG change is conveyed by the fringe of the distribution, not by the most prominent activity, so that a measure of central tendency (like the peak power frequency) cannot convey the necessary information.

sufficient information to correctly interpret the significance of the changes. Changes similar to those of figure 4*A* occurred in 50% (9 of 18) of cases in which an inhalational induction was used and suggest that attempting to monitor ischemia using the peak power frequency would result in a high incidence of false-positive warnings.

A different, but no less important form of distortion can occur when the EEG is averaged over time (for trend analysis) and slow oscillatory activity is present. Such activity is observed most commonly during burst suppression. Figure 5*A* shows an example of the power spectrum of such burst-suppression activity. When the same data are replotted with the time scale compressed in figures 5*B* and 5*C*, the characteristic pattern of activity and silence first is slurred and then eliminated entirely. This distortion can occur no matter which technique of monitoring the EEG is utilized, provided that the duration of averaging for the trend analysis is sufficiently long. In addition, Fast Fourier Transformation, the heart of power spectrum analysis, has certain averaging characteristics inherent in the computation. Accordingly, computation of the power spectrum using a long epoch (15–30 s) will produce the same type of distortion of burst-suppression activity that is seen in figure 5*C*. Such distortion is undesirable and demonstrates the importance of utilizing short (2-s) epochs rather than longer ones when performing power spectrum analysis.

The variety of anesthetics and anesthetic states used in this study suggest that multimodal power spectra are rather common during anesthesia. Multimodal EEGs were recorded during anesthesia with three common potent inhalational agents with and without nitrous oxide as well

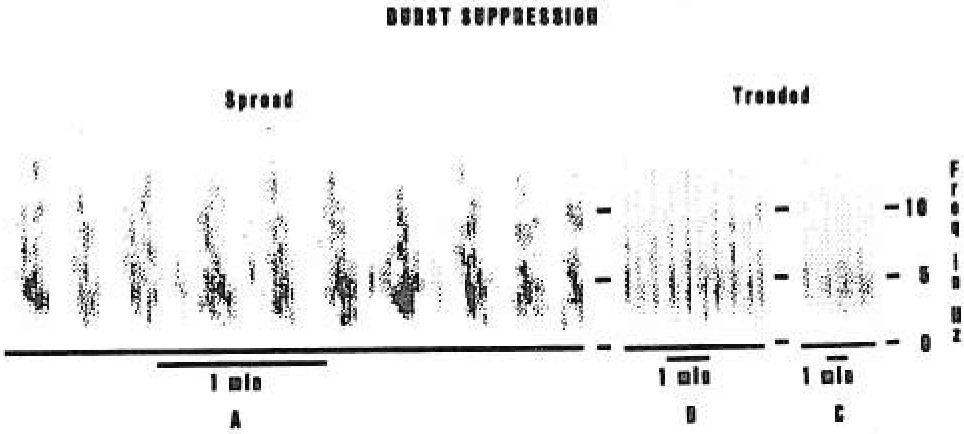

FIG. 5. Distortion of burst suppression by trending. This DSA of burst suppression was recorded during hypothermic (28° C) anesthesia with isoflurane (with cardiopulmonary bypass). The identical data are plotted in all three panels, and the blurring produced by trending is evident. Long-epoch (15–30 s) power spectrum analysis will produce exactly the same distortion as that shown in C, preventing recognition of the burst-suppression pattern.

as during anesthetics with fentanyl. The observation of such spectra in 37% of patients during the relatively stable anesthetic state before cardiopulmonary bypass suggests that sharp transients of anesthetic depth (such as the induction of anesthesia) are not necessary for these spectra to occur. Neither are the unphysiologic conditions of hypothermic extracorporeal circulation necessary, although the frequency of bimodal spectra during cardiopulmonary bypass may have important implications for the use of univariate descriptors of the EEG in assessing cerebral condition during bypass.

Burst suppression occurred in only one normothermic patient, who also was receiving high concentrations of enflurane. This undoubtedly reflects the clinical practice of utilizing muscle relaxants rather than inhalational anesthetics for muscle relaxation. Nonetheless, burst suppression occurs at clinically useful levels of isoflurane anesthesia (approximately 1.4 MAC)[14] and thus is likely to be observed when monitoring the EEG during an isoflurane anesthetic. When hypothermia is added to isoflurane, the incidence of burst suppression increases, with five of eight patients receiving isoflurane during hypothermic cardiopulmonary bypass displaying such a pattern. Although less common, burst suppression also was observed during hypothermic anesthesia with fentanyl and halothane.

While univariate descriptors do not contain as much information about the EEG as either the unprocessed tracing or its power spectrum, their effectiveness as monitors is dependent upon other factors, including the information desired, the risk of acting on misinformation (whether false negative or false positive), and the ability of another technique to provide the correct information. Even for such gross EEG events as hypoxia, the false-negative and false-positive rates for univariate descriptors are unknown, although one report suggests a false-negative rate of 18%.[15] In more recent work in patients undergoing carotid endarterectomy, Rampil has described a 30% incidence of EEG events unrelated to manipulation of the cerebral blood vessels[13]; however, no independent measures of cerebral blood flow or the unprocessed EEG were obtained so that true-positive and false-positive events could not be differentiated. When looking for more subtle EEG changes, such as those produced by hypothermia, univariate descriptors have proven unreliable.[16] In light of such findings, the validity of univariate descriptors as monitors cannot be assumed, even though the unprocessed EEG from which they are derived may be accepted as the "gold standard."

In conclusion, the incidence of multimodal patterns of EEG activity raises serious questions about the general applicability of univariate descriptors of EEG activity. No univariate descriptor tested served as a consistently adequate representation of the EEG power spectrum, and it is unlikely that any single descriptor could satisfactorily convey the complex patterns observed in the power spectrum analysis. Furthermore, excessive averaging over time may obliterate burst-suppression activity, giving the impression of continuous EEG activity when such activity is not present. Because methods of simplifying the EEG can mislead the observer about the nature of the EEG activity present, extreme care must be utilized to develop and validate methods of intraoperative EEG analysis.

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