Effect of Epoch Length on Power Spectrum Analysis of the EEG

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To study the effect of epoch length on the variability of power spectrum analysis of the EEG, 22 64-s segments of EEG were analyzed using epoch lengths of 2, 4, 8, 16, and 32 s. Nine of these segments exemplified EEG changes during transient anesthetic states or surgical conditions. Epoch-to-epoch variability was computed within frequency bins for all segments, and ANOVA with hierarchical classification was used to determine the length of the EEG segment necessary to identify a statistically significant change in those EEG segments recorded during changing conditions. In 16 segments, the epoch-to-epoch variability with power spectra were computed using 2-s epochs was significantly less than the variability when power spectra were computed using longer epoch lengths. In five segments, no significant difference existed between the variance at 2-s epochs and longer (4-s) epochs. In one case, an EEG containing a burst-suppression pattern, the variability was significantly increased when 2-s epochs were used. Analysis using 2-s epochs also identified changes more rapidly than analysis using any longer epoch length in eight of nine segments, and the differences were clinically significant as well (over 30 s faster when 2-s epochs were used instead of 16-s epochs). These findings suggest the preferability of short epoch lengths when power spectrum analysis is used for intraoperative EEG monitoring. (Key words: Brain: electroencephalogram. Monitoring: electroencephalography.)

Power spectrum analysis has been applied to the electroencephalogram (EEG) recorded during anesthesia since 1969.1 The development of practical display techniques and inexpensive microcomputers has made intraoperative use of this complex analysis possible, and a variety of commercially available monitors now employ power spectrum analysis. The mathematical inverse relationship between epoch length and the resolution of the resultant spectrum is well known; however, despite the use of epochs between 2 and 64 s in length, no study has been performed to investigate the effect of variation in epoch length on the analysis of the intraoperative EEG. Because the longer epoch is based on a larger sample of EEG activity, one might expect less epoch-to-epoch variability when longer epochs are used for power spectrum analysis. The more precise resolution obtained with longer epoch lengths might allow the identification of small shifts in EEG activity, offering a second reason for this technique to be preferable. Alternatively, the longer epoch length increases time delay before the display of new information and reduces the number of epochs available for intraoperative decisions.

This study was undertaken to examine the relative importance of these two alternative lines of reasoning. Specifically, this study was performed to determine the effect of epoch length on epoch-to-epoch variability and on the speed with which a change in the EEG can be identified using statistical tests.

Materials and Methods

From a variety of research studies, 22 segments of EEG were selected for analysis. These were chosen to be as representative as possible of intraoperative EEG recording during routine monitoring practice, thus the recordings included examples of awake alpha rhythm, EEG slowing due to cerebral ischemia during cardiopulmonary bypass, and EEG activity during a variety of anesthetic techniques during both steady state and transient conditions. Ten of the segments were recorded using a bandwidth of 3–35 Hz; a 1–70 Hz bandwidth was used for the remaining 12. Nine segments were specifically chosen to represent the EEG during rapidly changing conditions of anesthetic concentration, surgical stimulation, or during the onset of cerebral ischemia during extracorporeal hypoperfusion. Samples were not edited to remove isolated artifacts, although heavily artifact-laden recordings were not selected for analysis.

Each EEG segment was 64 s in length, and was digitized at 128 Hz, yielding 8,192 data points. Each segment was then analyzed five times, as two 32-s epochs, four 16-s epochs, eight 8-s epochs, 16 4-s epochs, and 32 2-s epochs. A mean square estimate of the variance within frequencies (epoch-to-epoch variance) was computed for each analysis. Since the same 64-s of EEG was analyzed, changes in variance in excess of those predicted by random chance must be due to the change in epoch length. To determine the statistical significant of the difference of two variances, an F-ratio (F-test) is used. Since there are ten possible pairs of five variances, ten F-ratios were computed for each 64-s segment. Statistical significance was assessed at $P < 0.05$ using standard tables.

The EEG segments recorded during changing conditions were used to assess the effect of epoch length on the speed of identification of changes in the EEG as follows. Each segment was digitized and processed as described above for epoch lengths of 2, 4, 8, and 16 s. Progressively longer portions of the EEG surrounding the midpoint of the segment were analyzed using analysis of variance with hierarchical classifications to determine if the difference between portions before and after the midpoint was statistically significant (fig. 1). A minimum of two epochs on
either side of the midpoint must be compared for the statistical analysis, and two epochs (one on each side of the portion already tested) were added to the analysis with each successive iteration. This technique simplifies the analysis by ensuring that equal numbers of epochs are being compared. Although the use of a baseline segment of fixed length would more closely resemble the way in which a change is identified in clinical practice, the comparison of differing numbers of epochs of power spectra would greatly increase the complexity of the statistical analysis. Since there is no clear benefit to this more complicated approach, the simpler symmetrical analysis was utilized.

Results

The results of the F-tests of epoch-to-epoch variance are listed in table 1, which itemizes the number of significant differences in epoch-to-epoch variance which occurred when comparing epochs of different length. In 16 of 22 segments, analysis with 2-s epochs demonstrated epoch-to-epoch variability which was statistically lower than the variability computed using any other epoch length ($P < 0.0001$) (fig. 2). In five of the remaining six analyses, the differences in variance did not achieve statistical significance. In only one case did analysis with other than 2-s epochs reduce the variability. This case involved burst-suppression with a 16-s pattern of burst and suppression activity (fig. 3).

Table 2 summarizes the effect of epoch length on the length of the EEG required to identify a change. The times reported do not include the baseline segment. In eight of the nine cases, the analysis with 2-s epochs identified significant differences before such a difference was demonstrated by analysis with longer epochs ($P < 0.02$). Exclusive of the baseline, 5.8 additional seconds of EEG were required to identify a change when 4-s epochs were used instead of 2-s epochs, ($P < 0.001$ by paired $t$ test). This difference rose to 15.5 s when 8-s epochs were used for analysis, and 30.7 s when the analysis was performed with 16-s epochs. For comparisons with 8- and 16-s epochs, these values represent “best case” estimates, assuming that all cases of non-significant comparisons would achieve statistical significance with the addition of the minimal amount of EEG data in each case.

Discussion

The application of power spectrum analysis to the EEG involves a number of implicit assumptions regarding the statistical nature of the EEG. Although these assumptions are rarely, if ever, actually satisfied, they are often approximated sufficiently closely to allow the application of this standard analytical technique to the EEG. Short-epoch analysis entails an additional statistical assumption—namely, that a brief segment of the EEG is truly representative of the EEG as a whole. Causal inspection of the EEG recorded during anesthesia (fig. 4) often reveals a complex pattern of activity in which brief episodes of different patterns appear interspersed. Since the eye is drawn to the differences between the brief periods of homogeneity, one receives the impression that brief segments of EEG are not representative samples, suggesting that the statistical sampling of the EEG which is inherent when using short-epoch analysis may not be valid. This impression has been supported by studies in awake patients which suggest the desirability of 20–30 s epochs.

The results of this study of the epoch-to-epoch variance demonstrate that the sampling error suggested by casual inspection does not occur when the entire EEG segment is analyzed. Instead, the reduction in epoch-to-epoch variance observed as the epoch length is reduced suggests

![Fig. 1. Sequential comparison of epochs. To identify the length of the EEG needed to identify a change, equal numbers of epochs before and after the midpoint of the segment were compared. The initial comparison was performed using four epochs, two before and two after. Subsequent comparisons were performed using two additional epochs, one added to each portion before and after the midpoint.](image-url)
FIG. 2. Reduced variability with short-epoch analysis. A contains a 64-s segment of EEG. B displays the average power spectra for this EEG when computed using 2-s and 16-s epochs. Power is plotted in units of intensity, $\mu^2$/Hz, which normalizes for the different number of points plotted for 2-s and 16-s analysis. C displays the mean square estimate of the variance for each component of the power spectrum on a relative scale. The mean square estimate of variance for the 16-s epochs is about 25% larger (on average) than the variance when 2-s epochs are used. This EEG was recorded during cardiopulmonary bypass at approximately 35° C with halothane anesthesia present.
**Fig. 3.** Increased variability with short-epoch analysis. A contains a 64-s segment of EEG with a repetitive 16-s pattern of burst-suppression activity. There is a brief artifact present (labeled "A") in the final few seconds of the EEG, which was recorded during cardiopulmonary bypass of 28°C with isoflurane anesthesia. B displays the average power spectra (in $\mu V^2/Hz$) computed from the EEG using 2-s and 16-s epochs. C displays the mean square estimate of the variance for each component of the spectra on a relative scale. The very high variance with 2-s epochs occurs because about three out of every four 2-s epochs are computed from the suppressed portions of the EEG and one is computed during the burst of activity. The 16-s epochs show reduced variance because each epoch contains both a period of burst and suppression and, thus, all the epochs are similar.
that 2-s epochs are statistically acceptable samples of the EEG during general anesthesia, and, thus, intraoperative monitoring may use an epoch this short without fear that epochs will appear highly variable due to sampling error. This conclusion would be tenable even if the epoch-to-epoch variance did not vary with epoch length; the observation that analysis with longer epochs significantly increases variability in most cases demands additional explanation.

It appears that the increase in variability when the analysis is performed with long epochs arises from the resolution by this technique of small frequency shifts which are not resolved using short-epoch analysis. Consider, for example, the average spectrum derived from one 8-s epoch containing a 100 μV²/Hz component at 10.125 Hz and one 8-s epoch containing a 100 μV²/Hz component at 10.375 Hz. The average spectrum would contain two 50 μV²/Hz components and a large variance. Since analysis with 2-s epochs cannot resolve a ¼ Hz shift, the average power spectrum derived from these same signals using 2-s epochs would contain a single 100 μV²/Hz peak between 10 and 10.5 Hz with zero variance. Obviously, as long as the resolution is adequate for the identification of EEG changes associated with changes in brain function, any increased resolution obtained by longer epochs is “empty resolution” and of no clinical value. Indeed, since it increases the variability it is undesirable. Previous work has identified EEG changes of 0.5–1 Hz in the alpha rhythm which are associated with the development of amnesia during anesthesia induction, and resolving such differences demands the use of epochs of 2 s as a minimum.

From a practical standpoint, the use of short epochs would be expected to produce more rapid detection of a change in the EEG than would be expected when analysis is performed using longer epochs. Not only is that conclusion supported by the second portion of this study, but the differences in time required to identify a change are clinically significant as well as statistically significant. The inability of analysis using longer epoch lengths to identify significant differences in cases when differences were identified with short epoch lengths raises serious questions about the efficacy of monitors which utilize epochs in excess of 4 s in length. Even when analysis using longer epochs was able to identify a statistically significant difference, an additional 30 s or more of EEG was required to make the determination. Although ischemia of this duration is unlikely to produce clinically detectable neurologic deficit, such a delay in the determination of ischemic change is unnecessary and undesirable. In particular, such a delay eliminates speed of diagnosis as one of the major advantages of the EEG for monitoring cerebral ischemia.

Burst-suppression, with its slow rhythmical variation, would be expected to represent an exception to these conclusions; and it does. The epoch-to-epoch variance associated with this pattern of EEG activity increased significantly as progressively shorter length epochs were used for analysis. This result provides some reassurance that this technique of analysis is sensitive to the sampling error produced by inadequate epoch length, but it also offers an argument against using short epochs for routine intraoperative monitoring. Fortunately, burst-suppression is readily identified in the unprocessed EEG and also when short-epoch power spectra are displayed for monitoring. Thus, there is little concern that serious confusion will result from the application of short-epoch power spectrum analysis when burst-suppression activity is present.

Despite the demonstration that short-epoch analysis of the power spectrum is preferable for intraoperative monitoring, care must be used in the extrapolation of this conclusion. If future research demonstrates a need to resolve ¼ Hz changes, then a 4-s epoch is necessary. If one is studying the phasic relationship of EEG activity, finer resolution of frequencies may reveal very different phase relationships and thus dramatically change the results of the analysis. In such a circumstance, the finer resolution obtained with longer epochs would be necessary. Thus, as different analysis techniques are applied to the EEG, it is imperative that the effect of the epoch length is explicitly analyzed and not simply extrapolated from these or other studies.

In conclusion, this investigation of the effect of epoch length on the power spectrum analysis of the EEG indicates that 2-s epochs are preferable for intraoperative monitoring. Epochs of this length allow more rapid detection of change by increasing the statistical reliability of the power spectral estimate. Although burst-suppression activity represents an exception to this rule, this pattern is readily identified by visual inspection of the se-
Fig. 4. Paroxysmal behavior of the EEG. A contains an EEG recorded during light isoflurane anesthesia. Inspection reveals irregular paroxysms of 10–12 Hz activity. Such bursts of activity might lead one to expect an increase in the variability when short epochs are used for power spectrum analysis; however, the mean square estimate of variance (B) shows no significant difference in the epoch-to-epoch variation when 4-s epochs were used. Similar results (not shown) were obtained when 2- and 8-s epochs are compared. For completeness, the power spectra are shown in C. This EEG was recorded during light isoflurane anesthesia.
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quentially displayed spectrum, and thus should not represent a contraindication to the general use of short-epoch power spectrum analysis for intraoperative monitoring.

References