THE USE OF ON-LINE TELEPHONIC COMPUTER ANALYSIS OF THE E.E.G. IN ANAESTHESIA


SUMMARY

Clinical application of electroencephalographic monitoring has generally been restricted by the complexity of on-line unprocessed data analysis. A technique has been developed which expands the applicability of clinical e.e.g. monitoring and presents the clinician with an e.e.g. spectral analysis designed specifically for readability in a dynamic environment. In this technique, one or more channels of electroencephalographic data are amplified, frequency-modulated and transmitted over a standard unprocessed, voice grade, direct distance dialling telephone line to a PDP-12 computer (8k memory). This information is processed in 4- or 8-second blocks using fast Fourier transform methods to present a power spectral plot of 0–16 Hertz bandwidth. Successive blocks of data are analysed similarly and plotted by computer direction to give a continuous record of the e.e.g. spectrum. These spectrum plots are simultaneously retransmitted over the same telephone line to the e.e.g. transmission location and plotted on a Y-T recorder. This system is currently being used in the operating room to guide the induction of safe, effective anaesthesia and ensure the adequacy of cerebral oxygenation.

As early as 1933, Berger demonstrated electroencephalographic changes associated with anaesthesia while Gibbs et al. (1937) later recommended observation of the electroencephalogram during surgery and Bickford (1950) developed an electronic system for measuring and controlling anaesthesia depth. Little use of these findings has been made, however, even though the need for accurately gauging light levels of anaesthesia, such as those frequently employed during cardiac surgery, has never been greater. Electroencephalographic monitoring in the surgical theatre for purposes other than assisting in the determination of anaesthesia depth, as well as in other clinical environments, has long been encouraged by specific e.e.g. research correlations. Few clinical extensions of the e.e.g. have come forth from the neurophysiological laboratory, however. This can be attributed in general to the conventional manner in which e.e.g.'s have been recorded and analysed while more specifically, the major factors restricting the clinical extension of the e.e.g. appear to be (1) the complexity and randomness of the primary information, (2) the specialized training required to analyse the data accurately, (3) the difficulty in correlating past events and trends in the e.e.g. recording to present ones during the dynamic conditions observed in most clinical circumstances, and (4) the prohibitive size of the recording equipment.

Recent advances in computer processing techniques have renewed interest in the clinical extension of electroencephalography. These techniques use common mathematical transformations to alter the characteristic e.e.g. display to the extent that the computer display is easily readable in a dynamic clinical environment. Stockard and associates (1972a,b) have recently demonstrated the value of these display methods in anaesthesia by using the computer methods of Bickford et al. (1971a,b; 1972) to monitor the e.e.g. of critically ill patients during cardiac surgery with cardiopulmonary bypass.

With this technology at hand, we have designed an on-line e.e.g. monitoring system that presents the anaesthetist with a dynamic, pictorial representation of cerebral activity in the surgical or intensive care environment. Telephonic transmission techniques are used to couple the mobile e.e.g. monitoring unit with a computer such that simultaneous two-way transmission of the primary e.e.g. data and its

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subsequent computer-directed presentation is continuously maintained on-line. The on-line computerized presentation of the e.e.g. displays three-dimensionally frequency, power and time to present the anaesthetist with an e.e.g. clinical monitoring system designed specifically to alleviate the classical e.e.g. problems by (1) simplifying the analysis of e.e.g. data, (2) accentuating trends in cerebral activity, and (3) reducing the size of the display equipment.

METHODS AND EQUIPMENT

Two essential components are present in this system. The first is the computer-processed compressed spectra technique of data analysis; the second is the telephonic transmission and display method used to telemeter simultaneously primary data and necessary control information over the facilities of the commercial telephone system.

Compressed spectra technique.

The compressed spectra techniques of Bickford and others (1972) have been modified to produce an on-line computational procedure with an output designed to be consistent with a simple telephonic modulation and transmission scheme.

A Digital Equipment Corporation PDP-12 computer is used to analyse continuously 4-second blocks of primary e.e.g. data. An analogue-to-digital (A/D) signal transformation is performed at the rate of 64 transformations per second, yielding a 256 sample point A/D conversion during the 4-second block of data entry. Next, a Fourier analysis is performed on this epoch of data, resulting in a power spectrum with 64 discrete components of 0.25 Hz resolution within a bandwidth of 0.25-16 Hz. The spectrum is then smoothed to assist in its readability and plotted over a 3-second period on the computer display oscilloscope. This 4-second analysis process is repeated continuously with no loss in primary data while the resulting spectra are plotted sequentially along the Y axis. The resultant plot is effectively time-compressed and given a three-dimensional appearance by preventing any line from being drawn behind a spectrum peak. A pictorial summary of this analysis technique is given in figure 1 and an example of the plot generated is given in figure 2, which shows a large percentage of the subject's e.e.g. power concentrated in the alpha band of the frequency spectrum with most of the activity occurring between 9.25 and 9.50 Hz. Continuous analysis and plotting of the e.e.g. in this form is maintained on-line with an average time delay between primary data occurrence and power spectrum plot of 7.5 seconds with no time delay greater than 11 seconds.

Computing flexibility has been designed into the software to the degree that the computer operator has control of data magnitude scaling and spectra line spacing. In addition to these controls, the maximum spectrum peak height is programmable. This feature limits the height of large amplitude spectral components caused by gross artefactual disruption of the e.e.g. while allowing observation of spectral events occurring later in time that would have been obscured behind large peaks. An operator-controlled programming option also exists which will cancel the “behind the peak” line suppression subroutine every 28 seconds. These alterations of the standard display were necessitated by the appearance of large amplitude slow-wave artefacts created by physical

![E.E.G Analysis and Display Method](image-url)
movement of the patient by the surgical team during surgery, by the electromagnetic interference of electrocoagulating devices and by the restlessness often observed in patients in the intensive care unit.

_Telephonic transmission and display._

Presently, this system transmits one channel of e.e.g. data over a conventional telephone line to a Digital Equipment Corporation PDP-12 computer located 12 miles distant while simultaneously a computer-generated compressed spectral plot is transmitted back over the same telephone line and plotted in the operating room or intensive care unit. Diagrammatically, the electronic scheme is described in figure 3. One channel of electroencephalographic activity is amplified using an integrated circuit, biological amplifier of our design with a $-3\,\text{db}$ bandwidth of 0.5-30 Hz and frequency modulated on a 790 Hz centre frequency audio carrier restricted to well within a maximum $\pm 10\%$ frequency deviation during modulation. This signal is then introduced into the wave-shaping and separation section of the system electronics where it is coupled with no loss in amplitude to a Bell System model 1000A data coupler—required by the American Telephone and Telegraph Company to assure electronically that all data users are conforming to prescribed specifications—but prevented from affecting the signals controlling the plotter. The data coupler is connected to an unprocessed, direct distance dial, voice grade telephone line (the least expensive and most common telephone line in the USA) accessible at any standard four-prong telephone connector. The signal is then transmitted 12 miles to the computer facility where it is decoupled from the telephone line using a similar 1000A data coupler. This 790 Hz signal is then actively filtered in two electronic stages to separate it from signals directed in the opposite telephone line direction and demodulated using integrated circuit phase lock loop techniques which result in the restoration of the e.e.g. to its original form. Compressed spectra processing is accomplished at the computer as described previously and the computer-controlled signals representing the start of the X axis sweep and the power/time Y axis, are frequency-modulated on carriers of 500 and 1700 Hz respectively, while limiting, again, the modulation deviation to within $\pm 10\%$. These carriers are linearly mixed to form a single frequency division.

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**Fig. 3. Block diagram of electronic system.**
multiplex signal (FM/FM) which is transmitted back over the same telephone line to the location of the biological amplifier. The 500 and 1700 Hz carriers are separated and demodulated using active filters and phase lock loop discriminators so that the original computer site oscilloscope display form of the signal is reconstructed. A Houston Instruments Y-T recorder, model 2200-3-6, is used to continuously plot the compressed spectra on-line in view of the anaesthetist (fig. 4).

Fig. 4. Portable anaesthesia monitoring system. Headbox is used to couple patient scalp electrodes to system.

RESULTS

The most easily observable consequence of this computerized analysis technique is its characteristic ability to accentuate slowly varying trends in the electroencephalogram. An example of this is given in figure 5. In this figure, hyperventilation is begun after 1 minute and 25 seconds of baseline recording from a normal patient who is relaxed with eyes closed. A typical 10.5 Hz alpha rhythm is predominant during this period since the electrodes have been placed to record the differential voltage variations between the right cerebral hemisphere frontal and occipital lobes. As hyperventilation begins, the alpha rhythm decreases in frequency and is replaced by large amplitude slow wave activity. This variation of the resting electroencephalogram corresponds to the hyperventilation-induced period of cerebral ischaemia secondary to the vasoconstriction caused by decreased carbon dioxide tension. This 60-second period of slowing is easily recognizable in the primary e.e.g. record but is difficult for the untrained electroencephalographic observer to quantify during its unprocessed real time presentation. The most significant advantage of this system is its ability to quantify subtle trends and present them in a readable form suitable for rapid analysis.

Fig. 5. The effect of hyperventilation on the e.e.g. Frequency slowing of the electroencephalogram occurs as a result of cerebral ischaemia secondary to vasoconstriction.

Figure 6 displays the spectral power variations of an anoxic brain. In this instance, a rabbit was anaesthetized with sodium pentobarbitone, intubated, curarized and ventilated. Three minutes of typical rabbit e.e.g. activity (theta activity) were recorded prior to the arrest of respiratory functions for 3.2 minutes which resulted in the electroencephalographic manifestations of anoxia. These include a slight initial increase in frequency—an increase difficult to notice on the primary trace—followed by large amplitude slowing, followed, in turn, by isoelectricity. When ventilation was re-established, spontaneous activity appeared as the hypoxia was reversed. This method of displaying cerebral activity assists in the identification of trends in frequency, or power, or both. During long periods of anaesthesia, changes in frequency or power may occur either slowly or suddenly and escape notice in the conventonal tracings. Such changes in frequency and power may be correlated to variations in cerebral blood flow or anaesthetic depth and consequently become most relevant to the patient’s care.
The induction of anaesthesia and its effect on the electroencephalogram is graphically displayed in figure 7. In this patient, who received morphine 10 mg as premedication, a continuous mixture of 50% nitrous oxide in oxygen and 2% halothane was administered after the baseline e.e.g. had been plotted. Stage 2 arousal was clinically observable and is recognizable in the compressed spectral plot between minutes 2 and 3 as an increase in e.e.g. frequency. Passage into stage 3 of anaesthesia was accompanied by a gradual decrease in frequency. As the halothane was turned off at minute 8½, the patient began to awake as indicated by an increase in primary e.e.g. frequency. When the halothane was turned back on, and after a 60-second period when data were not plotted, the patient returned to stage 3 of anaesthesia as the e.e.g. decreased in frequency and increased in power. The maximum allowable height of the spectral peaks is limited in the manner described previously, yet it should be noted that a considerable rise in e.e.g. power is generally observed when a large degree of slow wave activity is present.

Electroencephalographic abnormalities may be secondary to more fundamental abnormalities such as acute hypotension with associated inadequate cerebral perfusion which may lead to severe postoperative neurological complications if allowed to continue for prolonged periods. Seizure activity will first be noticeable in the electroencephalographic trace and may be especially difficult to diagnose clinically if neuromuscular blocking agents have been used (fig. 8). Direct observation of the e.e.g. as displayed by this system will allow early detection of cerebral dysfunction so that corrective action can be taken quickly.

**DISCUSSION**

There were a number of significant technical problems encountered in the development of the system. The original design had included the transmission of the analogue signals associated with both the X and Y axes of the plot. This scheme was desirable from the aspect of computer programming flexibility but was too susceptible to interference from harmonic signals and noise characteristically associated with telephone lines. The system in use now trans-
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SEIZURE

FIG. 8. Compressed spectra display of Metrazol-induced seizure in a rabbit. Conventional e.e.g. tracings are displayed to the right.

mits a pulse to indicate the start of the X axis at the computer and initiate a time sweep at the Y-T recorder. This method is less susceptible to noise and the type of harmonic interference observed earlier. The modulation scheme has remained FM/FM with information being transmitted in analogue form and digitally converted only at the computer.

The frequency response of the unprocessed, voice grade, direct distance dial telephone line is not closely specified in practice and is non-uniform within the telephone system while being functionally dependent on both position and time. The signal loss on the telephone cable used from the local exchange to the computer site is: \(-6.4 \text{ dbm}^*\) at 500 Hz, \(-8.1 \text{ dbm}\) at 1000 Hz, and \(-15.2 \text{ dbm}\) at 3000 Hz. Assuming the telephone line from the point of e.e.g. origin (operating room or ward) to the computer site displays a similar frequency response, there would be a difference of 17.6 dbm across a frequency bandwidth extending from 500 to 3000 Hz. This response severely limits the number of information carriers that can be frequency division multiplexed on this type of telephone line. To abandon this type of telephone line, however, would increase the cost of the system and its maintenance while decreasing its intrahospital portability and convenience of operation.

Non-linear bioamplifier gain characteristics have recently been included in an attempt to decrease the power spectral peak heights of slow wave artefacts and equilibrate commonly observed e.e.g. power peaks. Movement artefacts remain as a significant distraction and their elimination from this type of e.e.g. display is receiving attention.

The analogue modem type of transmission system employed has transmitted only one channel of e.e.g. data from the hospital to the computer and two channels for spectra data from the computer to the hospital. We are presently expanding the system to a more comprehensive monitoring system. Vital Indices Transmission and Analysis by Computer (VITAC) is an extension of the telephonic and computer concepts involved here and will incorporate computer-processed information on two or more channels of the e.e.g., heart rate, respiratory rate, and blood pressure. It is intended that VITAC will find wide applicability in such diverse clinical locations as the operating room, emergency room, intensive care unit, mental health facilities, neurology laboratories and various research facilities, since it will organize the presentation of vital signs and extend the flexibility of computer analysis to the clinician.

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REFERENCES


BOOK REVIEW


This booklet consists basically of a type of learning programme produced in collaboration with the department of audio-visual communication of the British Medical Association. It is designed to be used in conjunction with two tape recordings, and most of it could be considered as visual material to accompany a "taped" talk. In the greater part of the booklet one page is taken up with printed notes and diagrams, and the other side is left blank for any notes which the student may want to make; it is thus, as it says, a book for the personal use of anyone who buys it. There is also a short section on the organization of a hospital resuscitation service, a summary of resuscitation, and a self test with the answers provided at the end.

Right at the start it might be doubted that there is a need for a book of this very elementary standard for house officers, for it is, of course, to house officers that the book is addressed. It is easy to adopt a "holier-than-thou" attitude to such matters, but it does seem reasonable to hope that any medical man recently qualified in this country (or, for that matter, any medical man qualified elsewhere) will already have learned the lessons which it is attempted to teach here. After all, many house officers face the possibility of meeting a cardiac arrest even on their first day in their first post. The public has a right to demand that even the newly qualified will know the bare rudiments of resuscitation. There is little in this book that one could not reasonably expect a final year medical student to know.

Cardiac arrest is always a situation which is likely to cause panic to the newly qualified. In this situation complete clarity of teaching is required—the young and inexperienced resuscitator (doctor or nurse) requires a scheme of great simplicity to work with, and a series of simple "hat-pegs" on which to hang their knowledge. Unfortunately this book does not provide the clarity which is required, and tends to obscure the basic elements of resuscitation by introducing the not too helpful concept of primary and secondary procedures, using a flow diagram which not all will find particularly useful. A scheme based, for example, on the A B C of emergency resuscitation employed by the American Heart Association would be much easier to understand.

On many of the pages of text there are just a few words. It is not entirely satisfactory to open a book which has on one page only the words "start resuscitation" and "send for help" (admittedly arranged to make an impact for teaching purposes) and the page opposite blank for notes.

The illustrations, too, are largely unhelpful; a black-and-white sketch of the upper part of a man in bed with the words "Asleep or . . . ?" (p. 5) seems almost insulting, especially when, again, a whole page is left for notes on the other side. This would seem to be one of the more curious examples of an audio-visual aid technique. Does a doctor really need a full-page picture of an e.c.g. machine? Surely most will have seen one before. And looking at the book without the tape recording it is difficult to see why a picture of palpation of the carotid artery on p. 17 should follow a picture of external cardiac massage on p. 10.

There are several matters of technique here and there which might be considered contentious, but even if there were not it would be impossible to recommend this book. This is a pity because Dr Zorab's style of presentation on the tapes is a pleasure to listen to, splendidly informal without being undignified: he is clearly worth a much better text than this.

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