INSTRUMENTATION & TECHNIQUES

A simple electrode to record fetal EEG for optimal signal analysis

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A simple EEG electrode for intrauterine use in the human fetus is described. The stainless steel screw electrode possesses low noise characteristics, is constructed from commercially available material, and is easily attached to the fetal head during labor. Principles of optical signal analysis as an improved method of spectral analysis of the fetal EEG are also presented. The optical system provides visual display and hard copy output of the fetal EEG.

It is unlikely that a clear understanding of brain maturation, developmental changes, and the etiology of CNS damage can be achieved without determining more precisely the origin and functional significance of brain-wave changes that occur prior to birth (Twobin, 1970).

There is no consensus concerning human fetal electroencephalic patterns that are reflective of stressful events during labor and delivery. This precludes the establishment of clinical criteria for fetal well-being, distress, or brain damage based on brain-wave records. This may be due in part to restrictions on instrumentation.

Complex custom-designed fetal EEG electrodes have been reported by others (Mann, Swies, Duchin, & Newman, 1972). What is needed is an inexpensive, replaceable, simple EEG recording electrode for intrauterine application to the fetal scalp early in labor. The design should allow the practicing obstetrician who may wish to monitor the FEEG to easily construct and use the electrode. Also required is a sensitive analysis method capable of distinguishing subtle changes in fetal EEG frequency and amplitude characteristics that may not be readily observable by visual inspection or practical by scanning hours of strip-chart records. To provide ultimately for fetal intensive care or the prevention of brain damage, data analysis should be accomplished accurately and rapidly, with provision for central display to the obstetrical service.

We have recently developed a stainless steel screw electrode which satisfies the stated needs for recording

the human fetal EEG (FEEG) following rupture of the fetal membranes (Peltzman, Goldstein, & Battagin, 1973). This report describes the fabrication and electrical characteristics of this electrode. Also presented here is a discussion of the principles involved in optical processing of the FEEG as an improved method of spectral analysis to show the frequency content of a signal.

ELECTRODES

The screw electrode is fabricated from a Teflon-coated .45-in. stainless steel spring guide.¹ The catheter is cut into 25- to 30-cm lengths, and the ends are modified so that one end serves as the recording screw and the other end as the signal lead.

The solid steel stiffener that inserts into the center of the concentric spring is removed. The catheter is grasped 1 cm from an end with a fine-tipped pliers. The end coils are stretched to approximately four times manufactured length. The Teflon is scraped free, and a bead of solder is melted into the end at the Teflon-coated-to-stretched portion interface to just fill the center of the electrode and provide a stop for the stiffener. The stretched coil is then trimmed to 4 mm of exposed stainless steel coil

Fig. 1. Screw electrode (stainless steel) for recording FEEG. (Courtesy of American Journal of Obstetrics & Gynecology.)

Fig. 2. Polygraph tracing of activity recorded with stainless steel screw electrodes in saline solution.

Fig. 3. Polygraph tracing of activity recorded with rhodium-plated screw electrodes in saline solution.

Fig. 4. Polygraph tracing of activity recorded with gold-plated screw electrodes in saline solution.

(approximately three turns), which serves as the screw portion of the electrode. The Teflon is similarly removed from the opposite end of the catheter; this allows an alligator clip to be attached to the electrode to monitor the FEEG during labor.

In actual use, the steel stiffener is inserted through the electrode to the small solder bead to facilitate application to the fetal scalp. After the electrode is screwed into the epidermis of the fetal scalp, the stiffener is withdrawn. Figure 1 illustrates the screw electrode with the stiffener removed. Two such electrodes are attached 3-4 cm apart to the parietal area of the fetal scalp for bipolar FEEG recording. A maternal leg plate serves as ground. Successful insertion of the electrode into the uterus is achieved by passing the electrode through the cervix, using the examining fingers as a guide. The electrode is rotated several turns into the scalp.

An effort was made to determine the noise level associated with the use of a set of stainless steel screw electrodes and two other sets of electrodes each mechanically identical, except that one set had nickel chloride, silver, and rhodium electroplated in successive layers on the stainless steel (first two layers provide proper bonding for final coating). The third set had the identical bonding layers, with gold as the final layer.

Electrode pairs were individually immersed 2-3 cm into normal saline 0.9% and connected to the differential input of a Grass Model 7A high-gain low-noise preamplifier and chart recorder. The saline solution was connected to electrical ground. In both laboratory bench tests and clinical situations, the amplifier bandpass was adjusted to 1-35 Hz. Interelectrode distance in saline solution was 3-4 cm.

Final testing consisted of placing electrode pairs 3-4 cm apart into the parietal area of the scalps of the

investigators to record the bipolar EEG activity. A surface electrode adhered to the forehead served as ground.

Representative samples of polygraph tracings recorded with the electrodes immersed in saline are presented in Figs. 2, 3, and 4, which show activity from the stainless steel, rhodium-plated, and gold-plated electrodes, respectively. A comparison among tracings clearly reveals that the stainless steel set exhibited lower noise characteristics than the rhodium or gold electrodes.

Figures 5, 6, and 7 show the activity recorded from the adult scalps. Again, the stainless steel set revealed less noise than either the rhodium or gold electrodes.

The stainless steel electrode is being used exclusively in our current efforts to determine central influences on the fetus during labor. The risk of fetal scalp infection at the electrode implantation site is minimal. A localized mild erythema may mark the site of entry. Knowledge of the electrical properties of the electrode is also helpful in the consideration of automated computer FEEG pattern recognition programs, where it is important to distinguish electromechanical from physiologic noise in the brain signal.

OPTICAL SIGNAL PROCESSING

Important characteristics of a spectrum analyzer are its resolution and its ability to extract the significant characteristic frequencies of a signal from extraneous background noise. The capability of the spectral analyzer can be described in terms of its time bandwidth product or the number of data samples that are stored and, later, treated in the process of analysis. For

Fig. 5. Polygraph tracing of activity recorded with stainless steel screw electrodes placed in parietal area of adult scalp.

Fig. 6. Polygraph tracing of activity recorded with rhodium-plated screw electrodes placed in parietal area of adult scalp.

Fig. 7. Polygraph tracing of activity recorded with gold-plated screw electrodes placed in parietal area of adult scalp.

Fig. 8. FEEG optical analysis system. (Courtesy of *American Journal of Obstetrics & Gynecology*.)

conventional digital or analog analyzers, the number of samples may be only of the order of 10^3 digital words or analog values. On the other hand, 10^5 to 10^6 samples may be stored on a square centimeter of film, which is utilized in the optical processor. As in most systems, it is possible to trade off bandwidth vs the recording time interval. The resolution of the optical system is always of the order of 10^{-5} to 10^{-6} times the bandwidth.

Application to the analysis of fetal brain waves is indicated in Fig. 8, which schematically illustrates the optical processor.² In general, the tape-recorded FEEG signal is rerecorded in a two-dimensional time plane on film. After processing, the film is placed in the optical data processor and illuminated by a laser beam. A selected time window of data can then be viewed on a TV screen. The display may be orthographic, in which each frequency is displayed as a light dot in an X-Y field. The position of the dot is a measure of frequency and the brightness of the dot is a measure of electrical power of the frequency component. Using simple video processing methods, an isometric representation can be displayed. In the latter case, signal power is shown as amplitude in the Z plane, while frequency is measured by location in an X-Y field. Polaroid pictures can be obtained of either display.

Since the bandwidth in this case (fetus) is only 30 Hz, it is possible to record about 30 min of data on 1 cm^2 of film. The optical recording is simply a photograph of the face of a CRT, which is scanned in a manner similar to that of a TV tube with the intensity of the beam being modulated by the incoming signal.

The film is chemically processed in a few seconds with a Bimat technique and is then ready for spectral analysis in the optical processor shown in the lower portion of Fig. 8. The spectrum is focused on the face of a TV camera, which is used to produce displays on an orthographic TV screen and on a 3D or isometric screen at the right.

A minicomputer has also been tied into the system to display alphanumeric data on the TV screens.

A schematic presentation of the optical principles governing the formation of the spectrum or Fourier transform is shown in Fig. 9. This presents more details of the optical processor shown in the lower part of the system diagram of Fig. 4.

At the upper left portion of Fig. 9 is the previously recorded and developed film, which contains the information of the input signal stored as variations in optical transmittance. The square of film in the X-Y plane is a time exposure photograph made as the beam scanned the face of the CRT, as indicated by the parallel, equally spaced lines.

As an example, suppose the beam started at the upper right-hand corner of the aperture, or top of the first line, at time zero. Suppose that 0.1 sec was required to scan to the bottom of that first line. Then that the beam flew back, in negligible time, to the top of the second line, which was also scanned in 0.1 sec, and the process repeated with uniform displacement of successive lines in the negative X direction at a constant rate of 10 lines/sec. The signal will have been recorded in a two-dimensional time plane or raster

Fig. 9. Formation of Fourier transform.

mode—displacement along a scan line (Y direction) corresponds to a fine change in time (always less than 0.1 sec), while displacement from one scan line to the next (X direction) corresponds to a jump of 0.1 sec.

Of course, several hundred lines are scanned in the usual square centimeter format, and the line transmittance varies as the strength of the signal at the recording time corresponding to each point on the lines. However, let's temporarily consider the uniformly spaced lines to be of constant transmittance so that they form a simple grating.

If the grating is illuminated by a coherent monochromatic light source, such as a laser beam, then, at great distances, diffraction produces bright dots along a line such as the f_x axis perpendicular to the lines of the grating. There is a bright spot called the zero order on the line normal to the film plane. The next bright spot, labeled "line rate," corresponds to f_0 , the spatial frequency of the grating. Since the transmittance grating is not perfectly sinusoidal, there are also bright spots at the harmonics $2f_0, 3f_0$, etc., and because of symmetry, there are corresponding dots at $-f_0, -2f_0, -3f_0$, etc., in the opposite direction from the zero order. These line rate dots and a few harmonics can even be observed by looking through a grating at a small, distant light bulb in a darkroom.

By further calculations (Goodman, 1968), it can be shown that the Fourier transform of the modulated raster scan recording has the following properties: (1) The presence of any coherent component in the recording will produce a bright spot in the frequency plane. (2) That spot must lie on one of the frequency loci which form another raster indicated by the inclined parallel lines passing through the line rate spot and its harmonics. (3) Each spot is repeated periodically in the f_x direction with period f_0 . (4) In a manner similar to that of the time raster in the film plane, motion along a locus corresponds to a continuous variation of frequency, but motion in the positive f_y direction to the

next locus corresponds to an increase in frequency by exactly the line rate, f_0 .

Because of the periodicity in the frequency plane, the entire spectrum is displayed in any vertical half strip of width f_0 . It is convenient to use the shaded strip of Fig. 2 bounded on the left by the f_y —axis, below by the f_x —axis, and on the right by the vertical line $f_x = f_0$.

For the previously discussed recording where lines were scanned in 0.1 sec, the line rate is $f_0 = 10$ Hz. Therefore, the dashed segment of the locus passing through the origin contains positions of all frequencies in the interval 0-10 Hz. The next heavy segment upward contains the range of 10-20 Hz, the next segment, 20-30 Hz, and so on. If a frequency is not present, then the corresponding point in the transform plane is dark. However, as an example, the spot at the point P_0 , which lies $7/10$ of the distance across the third locus, indicates a signal component with frequency of 27 Hz. The intensity of the spot is proportional to the power of the original signal component.

Because of the large time bandwidth product of the optical processing system, much finer frequency resolution and improved signal-to-noise ratio are obtained. This method of spectral analysis provides additional diagnostic information about the EEG signal.

Comparisons based upon high data rates (Oliver, 1971) shows that optical spectrum analyzers cost only about 10^{-3} to 10^{-2} times as much as hard-wired fast Fourier transforms.

FEEG OPTICAL PROCESSING

We have been involved in quantifying possible drug effects upon the fetus during labor. Figure 10 illustrates isometric and orthographic optical displays of tape-recorded FEEG changes when comparison is made before (A) and after (B) a paracervical block is given to the gravid patient to alleviate pain. Coarse frequency, 0-27 Hz, is located in the vertical plane, and fine frequency at the rate of 0.4 Hz per line in the horizontal

Fig. 10. Isometric and orthographic displays of fetal EEG (FEEG). Display A represents FEEG activity prior to paracervical block (1% carbocaine, 240 mg) and Display B following block.

plane. Alphanumeric descriptors include the elapsed time (ET) from the start of the recording and the line at the low-frequency end of the displays reflects an operator-controlled sensor which, in this case, locates the line corresponding to the fetal heart rate artifact inherent in the data.

An operational system will require the accumulation, categorization, and statistical analysis of FEEG patterns under a variety of normal and suspected pathologic conditions. Automatic readout devices and real-time data processing with central display from Ampex Corporation, Redwood City, California, by data phone are realistic extensions of the present system.

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NOTES

1. United States Catheter and Instrument Corporation, Glenn Falls, New York.

2. Ampex Corporation, Research and Advanced Technology Division, Redwood City, California.

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