Chapter 3

Human Average Evoked Potentials: Procedures for Stimulating and Recording

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I. Introduction

Electrical potentials arising from the nerve cells of the human brain and recordable from the scalp can be divided conceptually into two types. The first type is a continuous series of potential oscillations which are not related in a specifiable way to sensory input. This spontaneous electrical activity is recorded as the electroencephalogram (EEG). The second type has a fixed temporal relationship to external sensory stimuli and is therefore said to be evoked by such stimuli. When potential changes evoked by repeated stimuli are averaged and plotted as a function of time after stimulus presentation, the result is termed the average evoked potential (AEP). There is abundant evidence that the AEP is indicative of the neural activity of the brain involved in the processing of sensory input. To the degree that we can learn to interpret this indicator, we should gain insight into sensory neural mechanisms operating in both the normal and pathological brain.

The first recording of evoked potentials in mammals is credited to Richard Caton who in 1875 recorded them directly from the surface of a rabbit's brain. It was 85 years later, and only about 10 years ago, that systematic analysis of the phenomenon became possible in man. The delay resulted from two factors. First, the layers of the brain case—meninges, skull, and scalp—attenuate the millivolt levels found directly at the cortical surface to microvolt levels at the scalp. It was not until 1929 that electronic amplification permitted Hans Berger to demonstrate that brain potentials could be recorded in man through the unopened skull. This discovery laid the foundation for clinical electroencephalography. However, much of the evoked activity is obscured by the larger potentials of the EEG. This adverse "signal-to-noise ratio" continued to limit human evoked potential research to components that could be distinguished in EEG traces or recorded directly from the brain during neurosurgical operations.

Systematic investigation of evoked potentials from the intact human head began to be feasible when Dawson (1951) suggested that those potentials regularly evoked by a repetitive stimulus could be discriminated from the irregularly occurring EEG potentials if all electrical activity subsequent to the stimulus was summated. The technique of summating, or averaging if summed voltage is divided by the number of repetitions, to extract systematic fluctuations from asystematic ones was used as early as the eighteenth century; Dawson's contribution was to apply the technique to human neurophysiology. Averaging enhances any activity which has a consistent temporal

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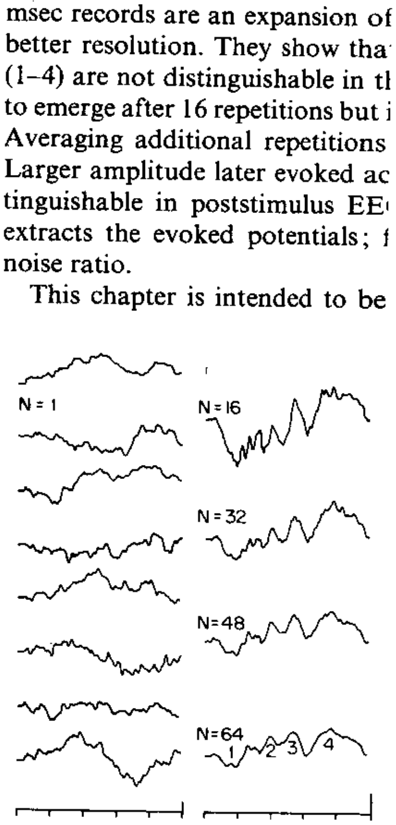

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relation to a recurrent event, i.e., is "time-locked" to the event, while concurrent activity inconsistently related to the event tends to cancel itself. Mathematically it can be shown that the time-locked activity (signal) summates directly as the number of repetitions whereas activity not time-locked (noise) summates only as the square root of the number of repetitions. The averaging technique, then, is a means of improving an initially adverse signal-to-noise ratio. Commercially built apparatus for averaging or summating evoked responses became available about 1960 and the bulk of research on human evoked responses dates from that time. Figure 3-1 illustrates the necessity of averaging to record the AEP. The traces in the first and third columns are examples of individual poststimulus EEG activity which contributed to the averages shown in the second and fourth columns. The 100-msec records are an expansion of the first part of the 500-msec records for better resolution. They show that small, shorter latency AEP components (1–4) are not distinguishable in the EEG record. Consistent activity begins to emerge after 16 repetitions but is still obscured by spontaneous potentials. Averaging additional repetitions progressively enhances the components. Larger amplitude later evoked activity (component 5) is inconsistently distinguishable in poststimulus EEG records. An average of 16 repetitions extracts the evoked potentials; further repetitions improve the signal-to-noise ratio.

This chapter is intended to be a practical guide to evoked response re-

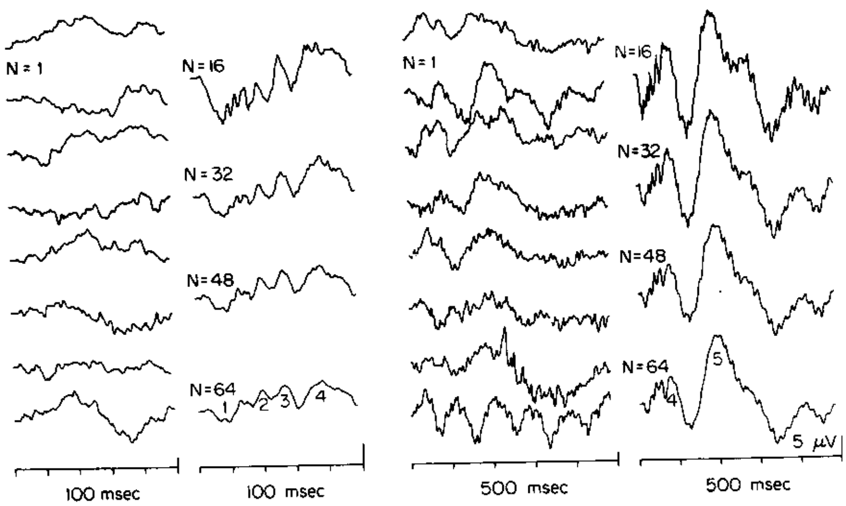

FIG. 3-1. Comparison of single poststimulus EEG records (1st and 3rd columns) and averages of increasing numbers of repetitions (2nd and 4th columns). Derivation: parietal scalp (P_3) to linked ears (A_1–A_2). In this and subsequent AEP records, positivity is upward at the scalp electrode. Stimulus: right median nerve shock delivered at start of records.

cording. There are many detailed discussions of most aspects of the technology of recording bioelectric potentials from the scalp but these are scattered throughout the engineering, chemical, physical, physiological, and psychological literature. My effort is to bring together practical information which I have found relevant. Where appropriate I have referred to commercially available equipment currently in use in my laboratory so that the beginning investigator may have some starting point for developing a recording system. In addition to the "hows" I have tried to answer the "whys" where I feel the knowledge will significantly increase the investigator's proficiency or flexibility.

When considering the characteristics of electrodes and amplifiers, it is useful to think of the AEP as being of two types: the so-called a.c. (alternating current) and d.c. (direct current) potentials. Alternating current potentials, like the EEG, fluctuate between positive and negative voltages. They can be recorded with conventional EEG electrodes and amplifiers. Direct current potentials are slow, usually aperiodic, changes which can be recorded from the scalp only by the use of specialized electrodes and amplifiers. This chapter will include recording methods for both a.c. and d.c. potentials since there is considerable communality between them. However, d.c.-evoked potentials, especially the contingent negative variation (CNV), are discussed elsewhere in this volume.

II. Electrodes

The same electrode characteristics required for a.c. AEP recording are also required for EEG recording and numerous discussions in considerable technical detail are available (e.g., Bureš, Petráň, & Zachar, 1967; Cooper, 1963; Cooper, Osselton, & Shaw, 1969; Geddes & Baker, 1968; Margerison, St. John-Loe, & Binnie, 1967; Walter & Parr, 1963). An electrode is a metallic connection between the complex physiological electrolyte of tissue and the recording circuitry. This metal-to-electrolyte junction or interface itself gives rise to potential differences between electrodes which can be quite large relative to the neuroelectric signals we wish to record. Potentials are developed because metal conductors in contact with a solution have a tendency to discharge cations into, and receive cations from, the solution. Whether the net result of this ionic transfer creates a positive or negative potential across the electrodes depends on the electrochemical activity of the metal and the cation concentration of the solution. Potential differences between electrodes are of two types: a bias potential, often incorrectly termed polarization (Edelberg, 1967), and true polarization.

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A bias potential results when differences in the properties of two electrodes cause an imbalance in the net electrode-electrolyte ionic transfer. Therefore, an important characteristic of electrodes is that their surface properties be as identical as possible, in other words, they should be of the same pure metal free from surface contamination. Under such conditions, because of the reasonably homogeneous electrolyte concentration of tissues, the net ionic transfer will be approximately equal at the two electrodes and to the extent that it is equal, no potential difference will develop between them. Considerations of cost, availability in pure form, resistance to oxidation and corrosion, and harmlessness to living tissue have indicated the use of silver, gold, and platinum for electrode metals.[1] Their purity and resistance to surface contaminations minimizes the generation of bias potentials. However, electrodes of these metals are polarizable.

Polarization requires the passage of a current through an electrode pair and results from the action of electrolysis occurring between the electrodes and the tissue electrolyte solution. When a voltage is impressed, positive ions migrate to the more negative electrode and negative ions to the more positive electrode. An electromotive force (emf) in opposition to that of the impressed voltage (a back emf) is thus developed and the electrodes are said to be polarized. Polarized electrodes favor the flow of current in one direction and resist the flow in the other direction; thus they may exaggerate or diminish the recorded current. The voltage recorded will be an interaction between the true biological potentials and the back emf developing at the electrode, resulting in "capacitative" distortion of the true potentials. A detailed discussion of electrode polarization is given by Schwan (1963) who states that polarization can affect a.c. signals such as the EEG and that the effect of the a.c. signal is to modulate the polarization potential. However, the modulation will be proportional to the a.c. current density if current density is kept sufficiently small. Electrode polarization impedances through a saline solution have been measured for a pair of platinum electrodes by Schwan (1965). The resistive component was relatively constant at approximately 100 Ω at frequencies of 10–100 Hz.

The current passage required for electrode polarization can come from internal or external sources. Modern instrumentation draws negligible current and this source may be ignored for scalp AEP work. Measuring interelectrode resistance with an ohmmeter is a significant source of external polarizing voltage and should be avoided. Indeed, a simple demonstration of polarization effects is to apply an ohmmeter across polarizable electrodes

[1] Margerison *et al.* (1967) have pointed out that these noble metals are chemically inert and technically do not conduct signals as low as those of scalp-recorded potentials in the same way as other metals.

attached to the scalp. The resistance reading will gradually increase as polarization occurs; reversing the leads will produce a sharp drop and then a gradual rise in resistance (Zablow & Goldensohn, 1969). Impedance is the more accurate measurement for a.c. potential recording; electrode resistance to a d.c. signal is frequently higher than electrode impedance to an a.c. signal. An impedance meter (1)[2] avoids polarization by applying an a.c. signal across the electrodes. Polarization can be minimized by having a reasonably large electrode surface which reduces current density of d.c. voltages across the electrodes. Furthermore, with a.c. potentials, the direction of current flow is continually reversing and to the extent that the reversal is equal and opposite, polarization will not occur. R. F. Thompson, Lindsley, and Eason (1966) point out, however, that polarizable electrodes can distort a.c. potentials if the proportional current flow is significantly more of one polarity than the other.

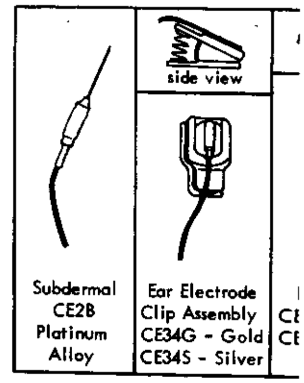
In summary, the use of gold, silver, or platinum electrodes kept free of surface contamination minimizes bias potentials. Furthermore, they are d.c. potentials and are blocked by the common use of capacitors at the inputs of amplifiers designed for a.c. potential recording (see Section V). Such electrodes are polarizable but polarization can be minimized by using surface areas large enough to keep current density low. Polarizable electrodes behave somewhat like capacitors (Cooper, 1963; Grass, 1948). However, this has been found to have a negligible effect on the recording of biopotentials in the EEG frequency range (Zablow & Goldensohn, 1969). Since evoked potential frequencies are in the EEG range or higher, this conclusion can be generalized to AEP recording.

While bias potentials and polarization effects may not affect AEP recording using high impedance capacity-coupled amplifiers, fluctuations in these potentials will be recorded and may be indistinguishable from legitimate biopotentials. The most effective means of avoiding such fluctuations is to minimize interelectrode impedance. The resistive component of this impedance is the easier to manipulate since the capacitative component is determined essentially by electrode-tissue properties. The smaller the interelectrode resistance, the less the range of resistive change and resulting potential fluctuations; and the smaller the percentage change of the total input impedance of the circuit.

Electrodes for a.c. AEP recording are commercially available in the form of gold-plated or silver disks for surface application and thin needles of sharpened platinum alloy wire for subdermal application.[3] Examples of

[2]Numbers in parentheses refer to equipment listed in the Appendix.

[3]Jenkner (1967) has reported encouraging results for EEG recording using electrodes made of conductive silicone rubber which require no electrolyte paste or jelly, no maintenance, develop no standing potentials, and adhere very tightly to the skin, minimizing electrode movement.



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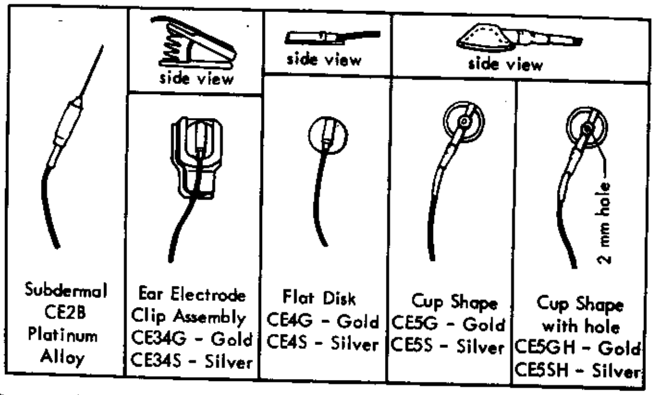


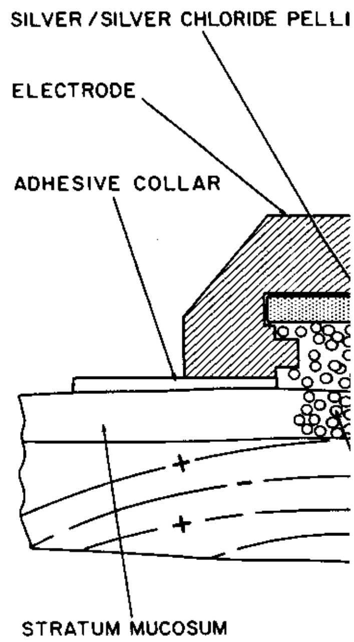
FIG. 3-2. Commonly used electrodes for a.c. AEP recording. (Courtesy Grass Instruments Co., Quincy, Mass.)

these electrodes are shown in Fig. 3-2. Silver electrodes can become tarnished by oxides and sulfides upon exposure to the atmosphere. Such contamination contributes to bias potentials. Gold, being more resistant to contamination, is preferred by many as producing fewer artifacts than silver. Disk electrodes properly applied should have impedances of 1 kΩ to 10 kΩ. Impedances below 5 kΩ are desirable; impedances over 10 kΩ require reapplication of electrodes. Subdermal (needle) electrodes may have resistances of up to ten times that of disks. Zablow and Goldensohn (1969) report that needle electrodes show much larger impedance changes with frequency in the EEG range than do surface disks. Impedance varied inversely with frequency, becoming as low as disks at 50 Hz (the highest frequency measured), rose significantly at 5 Hz, reaching approximately 0.14 MΩ at 0.5 Hz with a lagging phase shift of nearly 60 degrees. They concluded, however, that the alteration of the EEG was significant only for components below 1 Hz and only if the input impedance of the amplifier was less than 1 MΩ. They also found that needles are somewhat freer of potentials generated at the skin surface since they apparently make their best contact below these generators.

While needle electrodes are used in EEG laboratories and for AEP recording, primarily due to their speed and ease of application, their disadvantages should be kept in mind. First, since they tend to have somewhat higher interelectrode impedances, they are more susceptible to the generation of artifacts and the pickup of 60-Hz interference (see Section VII). Their use may be contraindicated for recording in unshielded areas where this kind of interference is prevalent. In such instances the use of disk electrodes with their generally lower impedances is preferable. However, we have recorded successfully in unshielded areas using needle electrodes. Second, they must be sterilized by autoclaving (see Section III). Finally, needles are not usually comfortable in nonscalp areas where reference electrodes are commonly placed for monopolar recording (see Section IV). Silver or gold disks are therefore used for the reference and the dissimilarity of these metals to the platinum needles may generate bias potentials. For reasons already stated, this is in practice ignored for the recording of a.c. potentials.

Polarizable electrodes cannot be used for d.c. recording because of the capacitative effect of the polarization. For similar reasons, capacity-coupled amplifiers cannot be used (see Section V). Direct-current recording techniques are mandatory for CNV experiments and are desirable whenever frequencies below 1 or 2 Hz are of dominant interest. These techniques require the use of "reversible" or "nonpolarizable" electrodes. A nonpolarizable electrode is one in which the passage of current does not qualitatively change the electrode's chemical composition and if a quantitative ion exchange occurs due to the application of a voltage, the change is completely reversible upon reversing the current. Metal electrodes covered with a poorly soluble salt of the metal in a solution containing anions of the salt meet these requirements. Some form of the silver-silver chloride (Ag-AgCl) electrode is the most commonly used. All physiological electrolytes contain chlorine ions and silver chloride is insoluble but easily formed on the surface of the silver either by electrolysis with a low voltage battery (faster procedure) or by the self-chloriding method (slower procedure) of leaving electrodes electrically connected in a saline solution. Methods for chloriding silver electrodes and for their maintenance are found in Cooper (1963), Margerison *et al.* (1967), and Walter and Parr (1963). A detailed discussion of Ag-AgCl electrodes is given by Janz and Taniguchi (1953). Various kinds of Ag-AgCl electrodes are commercially available which improve over the plain chlorided disk by providing a larger surface contact area to decrease current density. For example, the nonpolarizable electrodes in use in our laboratory (Fig. 3-3) use an Ag-AgCl pellet as a transducer element with an electrolytic reservoir between the electrode face and the pellet. When the electrode is applied, electrolyte is forced into the reservoir through holes in the electrode face, forming an interface between the skin and the pellet. The pellet is a porous, compressed mixture of Ag and AgCl powder. The porosity makes a larger amount of Ag-AgCl available to the electrolyte, fostering the development of a stable half-cell voltage between pellet and electrolyte. To the extent that such stability is achieved, there is no half-cell voltage artifact to shift the recording baseline (Beckman Instruments, 1965).

In summary, commonly used electrodes for AEP recording where frequencies below 1 or 2 Hz are not of major interest are silver or gold percutaneous disks or subdermally placed needles made from sharpened fine-gauge platinum alloy wire. The choice of which to use largely depends upon the circumstances of the individual experiment or the experimenter's preference in the tradeoff between ease of application versus somewhat higher



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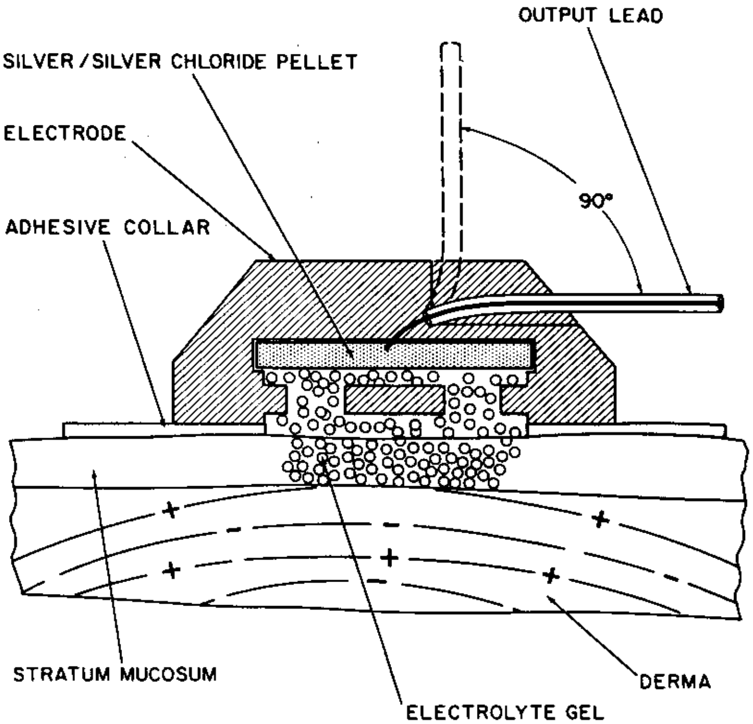

FIG. 3-3. Nonpolarizable electrode. Explanation in text. (Courtesy Beckman Instruments, Inc., Palo Alto, Calif.)

interelectrode impedance and the necessity for sterilization. Needle electrodes are not indicated for sleep experiments where the contact between head and pillow can cause painful movement of the needles. If very low frequencies or d.c. potentials such as the CNV are being investigated, nonpolarizable electrodes must be used.

III. Electrode Application and Maintenance

In terms of electrode application problems, there are two types of electrodes and two types of locations. The electrodes are surface or percutaneous (e.g., disks), and subdermal (needles). The locations are scalp and nonscalp. Scalp locations are usually hairy and the areas generally used as reference locations for "monopolar" recording are hairless. The simplest applications are needles to hairy areas and disks to hairless areas.

Between uses, needles should be examined for sharpness under an optical magnifier of 10 × or more and sharpened if necessary by hand on a fine grit stone. They should be soaked in a hemosolvent and then sterilized. Conn and Neil (1959) indicated the major hazard of needle electrodes for the transmission of viral hepatitis and pointed out that "cold sterilization" techniques such as immersion in germicidal solutions or ultraviolet light do not destroy the hepatitis virus. Early versions of needle electrodes would not withstand repeated heat sterilization but modern ones will. Steam sterilization before every use is a mandatory procedure.[4] In a study reported by Grass and Hazel (1962), electrodes were contaminated with different types of organisms similar in resistance to the hepatitis virus which can be transferred only through the human blood stream. Steam sterilization at 250°F for 15 min at 15 lb pressure sterilized 100% of the organisms. Recommended methods for needle electrode sterilization are steam autoclaving for 20 min at 250–260°F at 15–20 lb pressure. In our laboratory we use a small, countertop autoclave (2). Several needles are put in a test tube with cotton at the bottom to protect the tips. The wire leads are coiled outside the tube and fastened with sterile indicator tape (3). A cotton wad is jammed into the top of the tube and the assembly is autoclaved. After autoclaving, the needles are stored in their tubes undisturbed until use.

Before insertion of a needle, the scalp is rubbed with gauze soaked in alcohol or other sterilizing solution. Pulling on a tuft of hair or pinching the skin on bald scalps adjacent to the insertion point to lift the scalp, the needle is thrust firmly under the skin nearly parallel to the surface, imbedding the needle at least 8–10 mm along its length. A dull needle hurts; pain during or subsequent to insertion of a sharp needle is unusual and mild. When it occurs, it is usually in muscular frontal or temporal areas and can usually be eliminated by relocation 1–2 mm distant. For septic reasons, to protect their sharpness, and because contamination is conducive to bias potentials, the needles should not contact hands or other objects upon removal from the sterile tube. It is important to provide stress relief for needle electrode leads to prevent their pulling out and to prevent excessive movement which can cause pain. Gathering the leads at the neck and securing them to the skin or clothing with adhesive tape is adequate. Needles are not used in areas which are normally hairless because they tend to be painful.

Disk electrodes are easier to maintain. A thorough cleaning between each use and an occasional polishing is sufficient. They should be stored in a germicidal solution. Attachment to hairless areas such as forehead, nose,

[4] Needle maintenance problems would be eliminated by the development of disposable needles. A brief report of such an electrode was made by Miller, Shettel, and Parry (1963) but to my knowledge, disposable needle electrodes are not commercially available.

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earlobes, etc. is done with adhesive tape or washers. The skin is prepared by rubbing with alcohol or acetone to remove sebaceous oils and dead skin. Acetone is the more effective but may irritate sensitive skin, especially if rubbing is excessively vigorous. A superficial scraping of the skin followed by pricking the epidermis once or twice with a sterile hypodermic needle is very effective in reducing electrode impedance. To ensure good contact with the skin, disks require electrolyte cream or jelly which in excessive amounts precludes good adhesion by the tape. Experience will show the best compromise. We use cup-shaped disks, put the electrolyte in the cup, and then tape it in place.

A quick, neat, flexible method for applying disks to hairy areas is yet to be perfected. The choice of method involves compromise between ease and durability. After cleaning the area as above, we use one of the following methods. For shorter recording sessions (1–2 hr) a small mound of viscous electrode cream (4) is applied directly to the scalp after carefully parting the hair. The disk is imbedded into the cream and the edges of the depression are folded over the disk, holding it in place. As with needles, stress relief is important as disks attached in this manner are easily dislodged. The advantages of this method are ease and speed; the disadvantages are ease of dislocation, possible drying out of the cream if recording is prolonged, and moderate difficulty in removing the electrolyte paste from the hair. For long-term recording as in sleep studies, disk electrodes must be attached very securely. Collodioned electrodes properly applied will almost never pull off. Proper preparation to remove sebaceous or hair oil and scraping of the skin are especially important. The first trick is to apply just enough electrolyte to the electrode cup to make maximum contact with the skin but not so much that it squeezes out around the edge when the disk is pressed onto the scalp and interferes with the adhesion of the collodion. We find this balance easier to achieve with an electrolyte jelly (5) than with a paste. Disks are also available with holes in the cup through which electrolyte may be injected after application. The disk is pressed onto the scalp and held in place by, for example, the reverse end of a swab stick while a quick-drying, *nonflexible* collodion is dripped around its edges and the adjacent scalp and hair. A disposable syringe with blunted needle is useful to apply the collodion and a stream of air hastens drying. Pressure on the electrode can be removed when the collodion is partially dry but no stress should be applied before complete drying. The advantages of this method are durability and prevention of drying of the electrolyte. The disadvantages are longer application time and difficulty of removal, although an expert technician can apply and remove an array of collodioned electrodes in an amazingly short time. The collodion solvent is acetone which must be applied with a gauze sponge in fairly liberal quantities and which can cause skin irritation. It is usually very difficult to remove all the collodion from the hair without shampooing.

Different laboratories favor other methods for applying electrodes. Caps or harnesses may be convenient when the same electrode locations are used repetitively. Warm paraffin is sometimes used. It is kept just above the melting point in a controlled temperature bath and applied with gauze pads or swabs. The paraffin solidifies quickly at room temperature and prevents drying out. Jacobson, Kales, Zweizig, and Kales (1965) have described an electrode attachment method for sleep research which they consider better than the collodion method.

Nonpolarizable electrodes are exclusively percutaneous disks or pellets and theoretically may be applied with any of the methods used for disk electrodes. However, the necessary lack of low frequency filtering (see Section V,D) makes d.c. records more susceptible to artifacts such as slow potential shifts generated at the electrode-electrolyte-skin interface. To combat this, we find necessary a rigid electrode-to-skin connection. This is best achieved on the scalp with collodion and on a nonhairy skin with adhesive disks furnished by the electrode manufacturer. An impedance of 3 kΩ or less at 10 Hz is also important in avoiding such artifacts. At the risk of noting the obvious, a minimum of two nonpolarizable electrodes must be used for d.c. recording. In other words, one cannot reference a nonpolarizable electrode to a polarizable one. Nonpolarizable electrodes should be allowed to stabilize after application; our tests show about 20 min to be adequate. The maintenance and storage of nonpolarizable electrodes varies with the type and it is best to follow the manufacturer's instructions.

IV. Electrode Placement

An electrical potential at a given point can only be measured with reference to a second point. Thus, two electrodes are required to record scalp potentials. As will be discussed in Section V, the characteristics of "differential" amplifiers used for AEP recording are such that the amplifier output is the *algebraic difference* of all electrical activity occurring at the two electrodes connected to its input. Therefore, the placement of *both* electrodes is of critical importance in the interpretation of AEP records.

Comparison of AEP records between laboratories, and even within laboratories, has been hampered by a lack of electrode placement standardization. The importance of this problem for electroencephalography was recognized in 1947 when the First International Congress of Electroencephalography "recommended that an attempt be made to stabilize the placement of electrodes . . . to facilitate comparison of records taken in different laboratories and to make it possible to have more satisfactory communication

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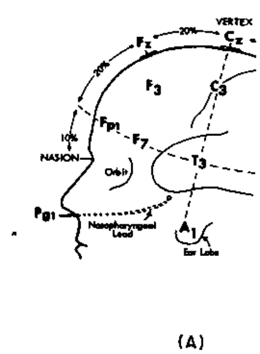

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FIG. 3-4. Locations of the 10–20 elec
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of results in the literature." The result of this effort is the "10–20 electrode system" of the International Federation of Societies for Electroencephalography and Clinical Neurophysiology (Jasper, 1958) which is coming into increasing use in EEG laboratories. In contrast, many AEP laboratories pay inadequate attention to, or even resist the suggestion of electrode placement standardization (Goff, Matsumiya, Allison, & Goff, 1969). There is, however, a trend for AEP investigators to utilize the 10–20 system, or at least to specify their locations with reference to adjacent 10–20 locations.

The locations of the system, shown in Fig. 3-4, are determined as percentages (10 or 20%) of the distance between the nasion and inion in the anterior-posterior plane, and the distance between the preauricular points coronally. The relation of the locations to the Rolandic and Sylvian fissures was estimated from anatomical studies. It was found that the position of the two fissures should be within about ±1 cm of that indicated on the diagrams, assuming careful measurement and lack of gross brain distortion due to pathology (Jasper, 1958). The steps for electrode location are well specified by Jasper (1958) and Cooper *et al.* (1969).

While standardization is desirable in the general case, the purpose of the experiment and the type of subject should be the primary consideration in choosing locations. Gibbs and Gibbs (1964) criticize the 10–20 system as being geometrical rather than electroencephalographic and not locating electrodes where they yield the maximum information. Rémond and Torres (1964) found the 10–20 system inadequate for topographical research and devised a system for closer electrode spacing. Hellström, Karlsson, and Müssbichler (1963) described the problems encountered in applying the 10–20 system to infants and smaller children. They presented a modified system using fewer electrodes with estimates of the relation of the electrodes to various parts of the brain based on X-ray films.

INTERNATIONAL (10-20) ELECTRODE PLACEMENT

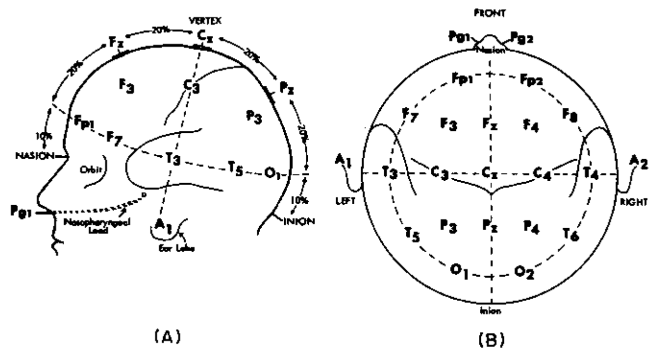

FIG. 3-4. Locations of the 10–20 electrode system. F, frontal; C, central; P, parietal; O, occipital. Odd subscripts = left side of head; Even subscripts = right side of head. Z = midline. (Diagram courtesy Grass Instruments Co., Quincy, Mass.)

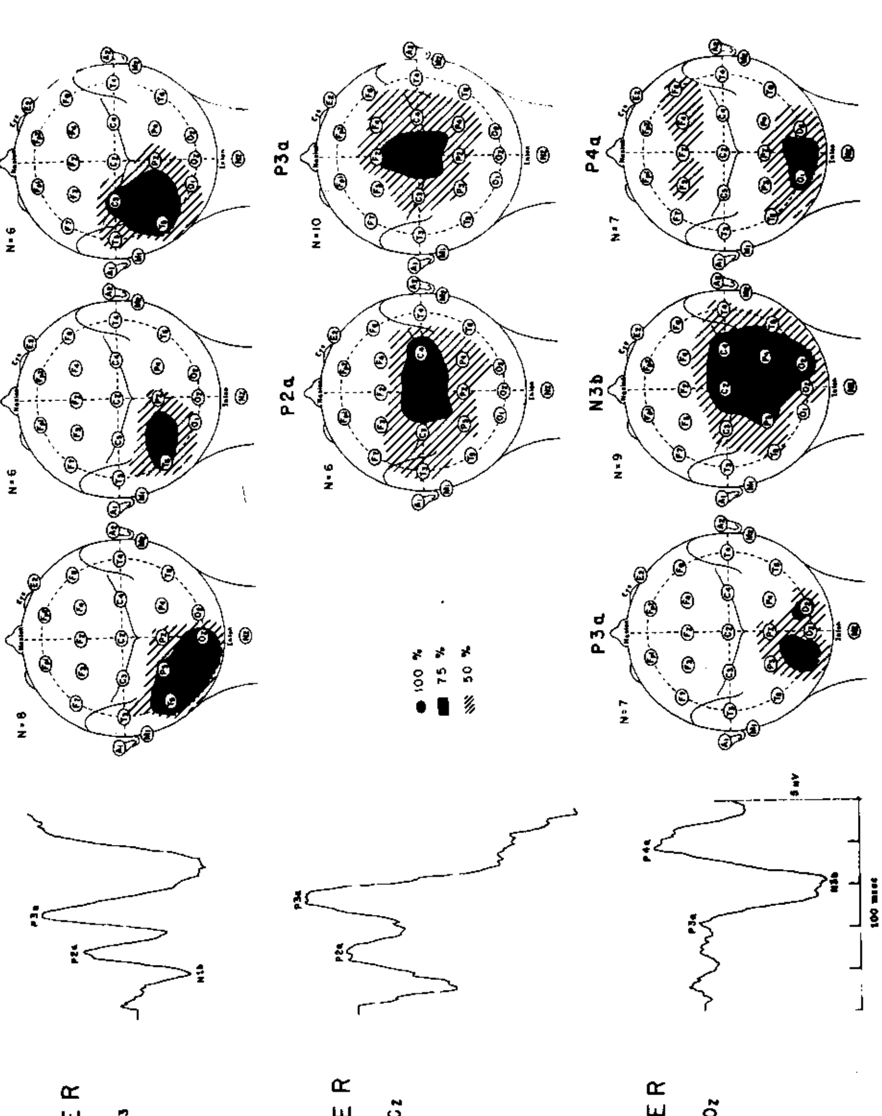

FIG. 3-5

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The primary considerations in choosing electrode locations for AEP experiments are first, the sense modality being studied; second, whether one wishes to study the total duration of the response or emphasize a particular latency range, e.g., early ($\leq$80–100 msec) versus late components; and third, the minimization of contamination by "extracranial" potentials. A selection on these bases requires knowledge of the focus and distribution of response components. Topographical studies for visual evoked responses (VERs) (Bourne *et al.*, 1971; Jeffreys, 1971; Jeffreys & Axford, 1972a, b; Rémond, 1964; Rémond & Lesèvre, 1965), auditory evoked response (AER) late components (Vaughan, 1969; Vaughan & Ritter, 1970), and somatic evoked responses (SERs) (Goff, Rosner, & Allison, 1962) have been reported. Goff (1969) and Goff *et al.* (1969) compared the distributions of cranial and extracranial AEP components seen during waking for all three modalities in the same group of subjects. SER stimuli were shocks to right median nerve at the wrist, AER stimuli were clicks via an earphone presented to the right ear, and VER stimuli were white light flashes presented in Maxwellian view (see Section VI,C) to the right eye. Relevant results from their study are shown in Fig. 3-5. Early SER components N1b, P2a, and P3a are maximal in the parietal area as would be expected since it is generally accepted that at least the earliest negative-positive sequence, N1b-P2a, represents input to, and the response of the primary somatosensory receiving area of the post central gyrus. The exact maximum amplitude focus on the scalp varies with the subject. In most subjects, the P_3 or P_4 locations for right and left side stimulation respectively are sufficiently close to the maximum for SER early components. There will not be significant contamination of SERs by myogenic potentials at these locations. The focus of SER early components to stimulation of leg nerves has been shown to be at the midline (Tsumoto *et al.*, 1972; Vaughan, 1969) as would be predicted from the known topological projection to postcentral gyrus in man.

If short-latency AER components represent neural activity in the primary auditory receiving area, we might expect their focus to be over the temporal areas T_3 and T_4. However, several studies (Celesia, Broughton, Rasmussen, & Branch, 1968; Mast, 1965; Ruhm, Walker, & Flanigin, 1967) as well as our own work (Fig. 3-5), have found them to be maximal in the vertex region, that is, around C_z in the 10–20 system. Their focus remote from the primary auditory areas and their similarity to extracranial "myogenic" po-

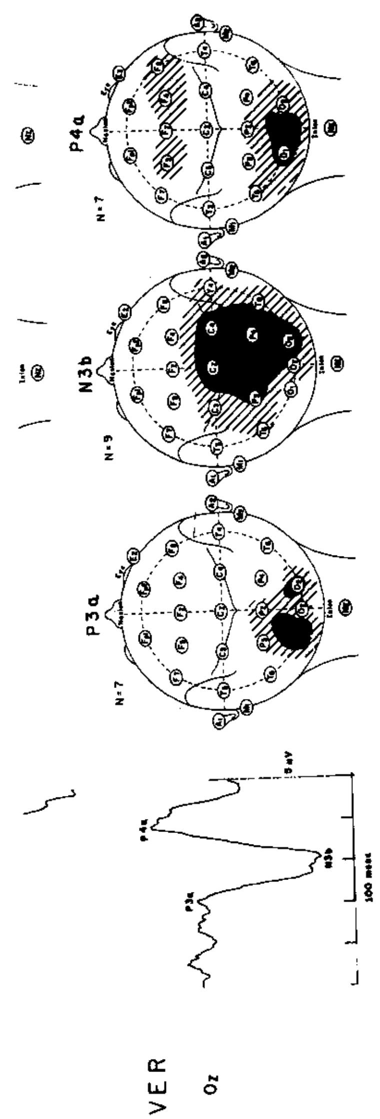

FIG. 3-5.

FIG. 3-5. Topographic distribution of early components of the somatic, auditory, and visual evoked response. The prototype waveforms shown at left are recorded from the 10–20 system electrode locations indicated referred to A_1. Distributions for each component are based on averaged data for the numbers of subjects indicated. Jagged edges indicate indefinite boundaries resulting from lack of delimiting electrode locations. (Modified from Goff *et al.*, 1969.) (In reproduction, the crosshatched 100% location filled in. Thus, those locations which appear to be missing from the 75% maps are actually the 100% points.)

tentials have raised two questions about these components. The first question is whether they are of neural origin. Ruhm *et al.* (1967) recorded simultaneously from scalp and subdural electrodes at a point near the vertex. They found the waveform and latency of responses from both electrodes to be highly similar. In a second subject, scalp and direct cortical responses from approximately the T_4 position also showed considerable similarity. They compared scalp AEPs in patients with hearing loss and in one patient with inactive semicircular canal function. On the basis of similarity of response from scalp and cortex in patients with normal hearing, the absence of response at subthreshold levels in the hypacusic group, and the presence of the response in the patient with semicircular canal deficit, Ruhm *et al.* (1967) concluded that there was clear early response componentry at the vertex which was cochleoneurogenic. The second question is whether they are generated in primary cortex. Celesia and Puletti (1969) concluded that the latency, duration, and configuration of scalp potentials were not comparable to those recorded directly from the human primary auditory cortex. Recent observations by Goff, Allison, Lyons, and Fisher (in preparation) that barbiturate anesthesia suppresses early auditory components recorded from the vertex in man support the contention that they are not primary auditory components.

Early components comparable in form and latency to those observed to somatic and auditory stimulation are not seen in the VER. The earliest VER component observed by us is a small inconsistent positivity peaking around 40 msec. It is followed by a larger, consistent negativity, peaking around 60 msec, and a positivity at 80–100 msec. These components are maximal in the parieto-occipital region (Fig. 3-5).

Later AEP components in all modalities are dominated by a large-amplitude negative-positive sequence with the peak of the positivity occurring from 150 to 250 msec depending upon the sense modality stimulated, the stimulus intensity, etc. The positive peak may be followed by another positive peak at 300 msec depending on the modality, the electrode location, and the experimental conditions. This diphasic response is diffusely distributed over the scalp, that is, it can be recorded to some degree from all 10–20 system locations. It is maximum at the vertex, or C_z, region and thus is called the "vertex potential." It is evoked in highly similar form by auditory, somatic, and visual stimuli and has therefore been regarded as being modality nonspecific. Recent evidence, however, (Stohr & Goldring, 1969; Vaughan, 1969; Vaughan & Ritter, 1970) suggests that some or all of the vertex potential may actually be generated in or near the primary receiving area for the given modality. Its maxima in the vertex region could result from volume conduction.

AEP research frequently requires that a minimum number of electrodes be placed where they will maximize the responses we wish to record. For

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example, the memory size and number of input channels available for most evoked response averaging devices limit the number of electrodes from which one can record simultaneously with adequate response resolution. Even with averagers having multiple input channels and generous memories, one may wish to minimize electrodes and record as a function of multiple stimulus parameters by directing responses to different parameters to different sections of memory. Optimum electrode placement requires knowledge of the focus and distribution of response components. In terms of the distributions shown in Fig. 3-5, the parietal location contralateral to the stimulus (P_3 or P_4) is within the area of at least 75% of maximum amplitude for SER early components. While the SER vertex potential is best recorded from C_z, as are the auditory and visual vertex potentials, if one were restricted to one location for the somatosensory system, P_{3-4} will serve for this component also. C_z is optimal for recording all AER components. VER component distributions show considerable variability but the occipital 10–20 locations, O_1, O_z, O_2, depending on retinal field stimulated, will record all VER components which appear to be of cranial origin. A possible exception is the vertex potential. Recent evidence suggests dual generators for the VER in this latency range, either at the occiput and the vertex (Garcia Austt & Buño, 1970; Vaughan, 1969) or in striate and extrastriate occipital cortex (Jeffreys, 1971; Jeffreys & Axford, 1972a, b). It is apparent, however, that three electrodes at P_3 or P_4, C_z, and O_1, O_z, or O_2, will record all components of auditory, visual, and somatic evoked responses. Goff et al. (1969) suggested these locations as standard for the respective modalities and for cross-modality comparisons. The benefit of such a standard would be that regardless of where else electrodes are placed, a minimum of one electrode would be common in different reports and comparisons of results within and between laboratories would be facilitated.

Earlier, I indicated that the placement of both electrodes was critical to the interpretation of AEP records. As the offspring of electroencephalography, AEP research has inherited much of its methodology and some of the attendant controversies. A major controversy is "bipolar" versus "monopolar" recording (Cooper, 1959; Cooper et al., 1969; Gibbs & Gibbs, 1964; Goff et al., 1969 and subsequent discussion; Mowery & Bennett, 1957; Osselton, 1965, 1966, 1969). If both electrodes are placed so as to record evoked activity, the result is a bipolar record representing the algebraic difference between the two electrodes. Monopolar[5] recording presumes the existence of an electrode location which is "inactive" with respect to the evoked neural potentials, but ideally, is equipotential to the "active" electrode with respect to myogenic, artifactual, and interference potentials (see

[5] "Monopolar" recording is a misnomer to the extent that it implies recording from one electrode (Storm van Leeuwen et al., 1966). The term *referential* or *common reference* recording is sometimes used.

Section VII). Such a reference would cancel these unwanted signals but would not alter evoked potentials occurring at the "active" electrode. Unfortunately, unequivocal proof of the existence of such a reference is impossible. If one cannot record potentials between two locations through a differential amplifier, it can mean that both locations are truly inactive or that they are equally active and thus cancel each other. The compromise has been to use locations which seem sufficiently remote from cranial generators to avoid recording AEPs. Examples are ear, chin, and nose. Goff *et al.* (1969) presented records from these locations referenced to the earlobe contralateral to somatic, auditory, and visual stimuli. Large, probably myogenic, evoked potentials were seen at the nose. Little evoked activity was seen at the chin or between the ears, but the chin is too susceptible to muscle activity to serve as a reference in most subjects. One ear, preferably that contralateral to the stimulus (Goff *et al.*, 1969), or both ears connected together, the so-called "linked ears" (A_1-A_2 in the 10–20 system) are frequently used references. Mowery and Bennett (1957) criticized linked ear electrodes because the ear with the lower electrode resistance is predominant and because they are likely to pick up activity originating in the temporal lobe. Garnesky and Steelman (1958) suggested a method for correcting unequal ear reference resistances.

Perhaps the best way to check the indifference of a reference location is to test it against an electrode which is completely off the head. The problem here is the large EKG which contaminates the records. Stephenson and Gibbs (1951) devised a "noncephalic indifferent" method which minimizes EKG in most subjects. Electrodes are placed over the right sternoclavicular junction and the seventh cervical spine. The two electrodes are brought to a common point which serves as the reference through variable 20 kΩ resistors. The variable resistors are adjusted to balance out the EKG. Gerbrandt, Goff, and Smith (1973) checked the isopotentiality of the linked earlobes for averaged movement potentials using this noncephalic indifferent. In some subjects, neural activity occurring in the Rolandic region was also recorded from the earlobes. When the electrodes were placed on the interior surface of the upper pinna, little or no activity was seen. Lehtonen and Koivikko (1971) tested the isopotentiality of the earlobe against a noncephalic indifferent for binocular flashes, binaural clicks, and median nerve shocks. The earlobe was active in some subjects for visual stimulation but inactive for auditory and somatic stimulation. The noncephalic indifferent was active for somatic stimulation. Their results are consistent with the conclusion of Goff *et al.* (1969) that the earlobe contralateral to a unilateral stimulus is the best compromise as a common reference point to compare AEPs across modalities. Unfortunately, the noncephalic indifferent is time consuming for routine recording, the EKG cannot always be el these unwanted signals but at the "active" electrode. Un-ce of such a reference is impos-veen two locations through a locations are truly inactive or l each other. The compromise ently remote from cranial gen-s are ear, chin, and nose. Goff ations referenced to the earlobe l stimuli. Large, probably myo-ose. Little evoked activity was chin is too susceptible to muscle jects. One ear, preferably that 1969), or both ears connected $_2$ in the 10–20 system) are fre-nett (1957) criticized linked ear ctrode resistance is predominant vity originating in the temporal ested a method for correcting

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adequately cancelled, and it does not cancel extraneous activity such as EMG from cranial musculature as well as a reference on the head. However, it can and should be used to assess activity at any intended reference for each subject under actual experimental conditions before the investigator can know the extent to which he is obtaining "monopolar" records. Some electroencephalographers favor the use of an "average" reference electrode (Cooper *et al.*, 1969; Goldman, 1950; Offner, 1950; Osselton, 1965, 1966, 1969) but it is not favored by AEP investigators.

As in the placement of the primary electrode, decisions regarding the placement of the second electrode so as to achieve bipolar or monopolar recording should ultimately depend on the purpose of the experiment. However, Goff *et al.* (1969) presented an example of differences in bipolar *versus* monopolar AEP records which varied with stimulus intensity and suggested that bipolar records are difficult to interpret in the absence of simultaneous monopolar records; that because of considerable differences in topographic distribution of various AEP components, scalp-to-scalp records may be essentially monopolar for some components and bipolar for other components of the same response; and that intersubject variability in component distribution would increase variability in bipolar records compared to monopolar records. They conclude, as have others (e.g., Davis, 1969; Gibbs & Gibbs, 1964; Vaughan, 1966; White, 1969) that *in the general case*, monopolar recording, always assuming that the "indifference" of the reference is carefully assessed, is preferable because the interpretation of records is simpler and interlaboratory comparisons of records is facilitated.

Two additional considerations favor monopolar recording: (1) As with the EEG (Knott, 1969), the polarity of an AEP component is important in interpretation of its neurogenesis. Abundant evidence from animal and human research shows that positive and negative phases of some evoked potentials are generated by separate neural events within the same cerebral structures or in different structures. Polarity in bipolar AEP records is usually meaningless without independent assessment of the contribution of each electrode from monopolar records, or unless one uses multichannel derivations from successive pairs in an electrode chain (e.g., Knott, 1969) which is frequently impractical because of limited input capacity of averaging devices. (2) In AEP recording systems where responses are stored in recoverable form, such as on analog or digital magnetic tape, simple computer subtraction of two monopolar responses provides the equivalent bipolar record. However, monopolar records cannot be derived from a bipolar record.

Arguing that monopolar recording is preferable in the general case is not to say that bipolar derivations are not valuable for specific purposes. The closer together two electrodes, the greater the cancellation of common ac-

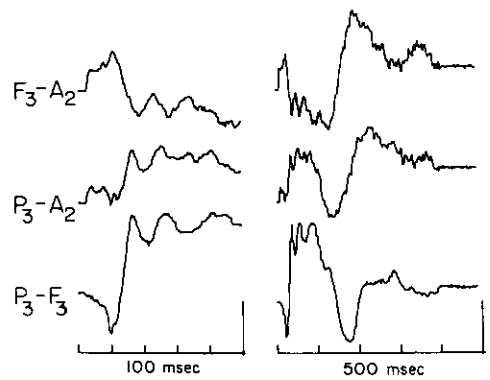

FIG. 3-6. Comparison of monopolar and bipolar records of SER early components anterior and posterior to the Rolandic sulcus. Additional explanation in text.

tivity. In the case of early AEP components with restricted distributions, it is possible to place a reference on the scalp close enough to record a larger percentage of the "noise" than from a nonscalp reference but little or none of the early evoked potential components. The effect is to significantly improve the "signal-to-noise" ratio and the resolution of small amplitude early components. A special case of improved resolution with bipolar recording results from the polarity reversal of SER early components across the Rolandic sulcus (Broughton, 1969; Broughton, Rasmussen, & Branch, 1968; Goff, Matsumiya, Goff, & Allison, in preparation). Figure 3-6 compares monopolar and bipolar records across the Rolandic sulcus for shock stimulation of right median nerve at the wrist. Early activity at P_3 is reversed at F_3 when both are referred to the contralateral ear. The diffusely distributed vertex potential with a positive peak at approximately 200 msec is similar in both recordings. The bipolar P_3–F_3 derivation summates the polarity reversal to enhance the early components; however, the vertex potential common to both locations is badly distorted compared to the monopolar records. Another application of bipolar recording is the localization of the source of an AEP component by the phase reversal technique common in electroencephalography (e.g., Vaughan & Ritter, 1970). There are, however, hazards in the interpretation of such records (Kooi, Tipton, & Marshall, 1971).

A consideration of great importance in the placement of electrodes is the possible contamination of AEP records from nonneural "myogenic" sources. Bickford (1964) first reported that potentials could be evoked in cranial musculature which mimicked in form and latency potentials considered to be of neural origin. Considerable research has subsequently been devoted to the "photomotor" (Bickford, 1964; Bickford, Jacobson, & Cody, 1964b), "sonomotor" (Bickford, Cody, Jacobson, & Lambert, 1964a; Bickford *et al.*,

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: Lambert, 1964a; Bickford *et al.*,

1964b; Celesia *et al.*, 1968; Cody, Jacobson, Walker, & Bickford, 1964; Mast, 1965), and "somatomotor" (Calmes & Cracco, 1971; Cracco & Bickford, 1968) responses, and the extent to which they may be confused with neurogenic responses. It is established that the greatest possibility of myogenic contamination occurs under conditions of unusually high stimulus intensity and muscle tension, conditions which are normally avoided in the AEP recording situation. Nonetheless, the prudent AEP investigator should be constantly aware of this possible source of extraneous potentials in his records. Knowledge of the focus and distribution of these potentials is of practical value in the choice of electrode placements. Goff *et al.* (1969) plotted the distributions of AER, SER, and VER components which they categorized as myogenic on the basis of intersubject variability in appearance and topography.

Finally, contact nasopharyngeal electrodes (see Fig. 3-4) are coming into increasing use for EEG recording from the mesio-basal surface of the temporal lobe (e.g., Bach-y-Rita, Lion, Reynolds, & Ervin, 1969; de Jesus & Masland, 1970; Mavor & Hellen, 1964). Smith, Lell, Sidman, and Mavor (in press) recorded auditory, somatic, and visual AEPs, and Smith, Allison, and Goff (1971) attempted to record potentials to odorous stimulation using contact nasopharyngeal electrodes. Lehtinen and Bergström (1970) have reported a nasoethmoidal electrode for recording from the inferior surface of the frontal lobe.

V. Amplification

A detailed discussion of amplifier circuitry is not included in this chapter for two reasons. First, many excellent ones already exist (Cooper *et al.*, 1969; Geddes & Baker, 1968; Malmstadt, Enke, & Toren, 1963; Middlebrook, 1963; Schoenfeld, 1964; Stacy, 1960). Second, in practice one needs only to know the functional characteristics and how the various adjustments affect these characteristics in order to select an appropriate amplifier, adjust it properly, and accurately interpret AEP records.

The "differential" (discriminating, balanced, push–pull) amplifier is universally used in AEP recording. The relevant characteristics of this type of amplifier are its input impedance, sensitivity, noise level, gain and frequency response, common-mode rejection, output impedance, and d.c. level. Gain, frequency response, common-mode rejection, and d.c. level are usually adjustable.

A. Input Impedance

The input circuit of an amplifier is basically a voltmeter. It determines the current flow through a fixed resistance, i.e., the voltage between one input and a reference point. If the reference is ground (earth), the amplifier has one, or a "single-ended" input. A differential amplifier measures the voltage between two inputs, both of which derive from electrodes placed on the subject. As with any voltmeter, it is imperative that the meter itself not alter the signal being measured. When the electrodes are connected to the amplifier, the input impedance is effectively in parallel with the impedance between the electrodes, thus creating a voltage-dividing network. If the input impedance is too low, it shunts the interelectrode impedance. Cooper *et al.* (1969) indicate that with an interelectrode impedance of 10 kΩ and an input impedance of 1 MΩ, the input signal will be reduced about 1%. The input impedance of modern differential amplifiers is in the range of 1 MΩ or more and signal reduction, if any, is slight and usually ignored. There are no adjustments for input impedance on commercial amplifiers.

B. Sensitivity

The maximum sensitivity of an amplifier is usually specified as the minimum input required to produce a specified output. The maximum sensitivity for an EEG machine, for example, is usually the minimum input (in microvolts) required to cause a full-scale deflection of the pens. In an IRIG compatible instrument, the maximum sensitivity is the input required to produce a minimum of 1 V peak to peak. IRIG is the acronym for Inter-Range Instrumentation Group who have specified a set of standards for use with guided missile telemetry and other space research applications (IRIG Telemetry Standards, 1969). The minimum sensitivity of the amplifier is usually specified in terms of the maximum voltage that can be applied to the input before the amplifier is driven beyond its linear operating range and distorts the signal (see Section V,C). Sensitivity in the microvolt range is required to record AEPs from the scalp; amplifier output ranges of ± 1–2 V are required to drive the analog-to-digital converters of most averaging devices and digital computers.

C. Noise Level and Distortion

Noise in a amplifier is any electrical activity at the output which is not a reflection of what is applied to the input. Thus it includes random voltage fluctuations inherent in resistors, tubes, and transistors, 60 Hz from inadequacies in filtering, isolation or shielding, etc. The inherent random voltage fluctuations are the only noise source which should be found in a properly constructed, properly operating amplifier. The noise level of an amplifier is specified in terms of microvolts of equivalent input. It is mea-

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sured by monitoring output with the inputs shorted together. The amplitude of the output noise divided by the gain factor (see Section V,D) is the input equivalent noise level of the amplifier. Thus, if the amplifier is set to a gain of 10,000 and 50 mV of noise is seen at the output, the equivalent noise level is 5 μV. Since noise is superimposed on the signal, the amplifier noise level limits the signal that can be resolved unless averaging is used. Commercial amplifier equivalent noise levels are in the 5–10 μV range. Signal-to-noise ratios can be improved by filtering so long as the filtering does not distort the signal (see Section V,D). Noise occurring in the first stages of an amplifier is more critical since it will be amplified by the later stages. Thus first and sometimes second amplification stage tubes and transistors are selected for low noise levels. Selected replacements are usually available from the amplifier manufacturer. There is a more extensive discussion of noise in Schoenfeld (1964).

Distortion in an amplifier is any qualitative difference between the input and output signal. A tube or transistor conducts current only within certain limits which define its particular operating range. Moreover, its output is not linearly proportional to its input over the entire operating range, but rather decreases gradually at the extremes. For tubes and transistors typically used in amplifiers, a graph of plate voltage output as a function of grid voltage input is an S-shaped or sigmoid curve. There is a range symmetrical about the midpoint of this curve in which output is linearly proportional to input. This is the linear operating range. A fixed voltage is applied to the grid to hold conductivity at this midpoint. This is called the grid bias. Output voltage fluctuates around this midpoint. If a symmetrical signal such as a sine wave is applied to the grid and the signal is so large as to drive the tube beyond its linear operating range, the peaks will be attenuated, producing distortion. If a symmetrical signal is so large as to drive the tube completely beyond its operating range, the signal will be "peak-clipped," that is, the tops of the peaks will be flat. If an asymmetrical overloading signal is applied, the peaks of one polarity may be attenuated or flattened, while the other polarity peaks will still be within the linear operating range and thus undistorted. If an excessive, nonfluctuating voltage is applied to the tube, effectively biasing it beyond its operating range, no conduction will occur, and the amplifier is said to be blocked. This is seen at the output as a large, steady voltage. On an EEG machine, for example, the pen remains at maximum deflection in one or the other direction until the excessive voltage declines and the amplifier "recovers."

For most AEP recording, a.c. amplifiers are used. In such amplifiers, capacitors are used to couple the input to the first stage grid and to couple successive amplification stages. This simplifies amplifier design and usage by blocking d.c. plate voltages and very slow potential drifts which would otherwise affect subsequent stages. This capacitative coupling causes the amplifier to pass only alternating signals. If an excessive voltage is applied to a capacity-coupled amplifier, one or more of the capacitors may become overcharged. The amplifier can no longer respond until the capacitor is at least partially discharged and this is another way in which the amplifier can be blocked. The time required for the capacitors to adequately discharge upon removal of the excessive voltage determines the "recovery time" of the amplifier. Another type of distortion is phase shift. This is a change in the phase relationship between input and output. A phase shift of 180° is a complete polarity reversal. There should be no distortion or phase shift in a properly designed amplifier operating at appropriate gain settings and within its linear frequency response.

D. Gain and Frequency Response

The terms gain and amplification are synonomous and refer to the factor by which an amplifier increases the output amplitude of an input signal. Frequency response refers to the range of frequencies (rates of voltage change) or the bandpass over which amplifier output is independent of frequency within specified limits. Gain and frequency response are the most important amplifier settings for AEP work and both should be specified in research reports. The frequency response capabilities of the typical a.c. amplifier range from a fraction of a cycle to frequencies well above those needed for AEP recording. Direct current amplifiers pass steady voltages but not frequencies much above 50–100 Hz. The most important frequency response characteristic of an amplifier to bear in mind is that the cutoff, that is, the limits of a specified bandpass, is not abrupt. In other words, if the high frequency filter setting[6] is specified at 1000 Hz, this does not mean that it amplifies all frequencies equally up to 1000 Hz but does not amplify 1001 Hz. Gain as a function of frequency at the limits of a given bandpass changes gradually; the term rolloff is used to describe this gradual decline. Another way of saying this is that the frequency response is not *flat* (equal gain for equal input as a function of frequency) within the specified limits of the upper and lower filter settings. The filter settings by convention specify that point in the frequency response curve of the particular amplifier where the gain is 50% of the maximum gain in the flat part of the bandpass. Sometimes they are specified in decibels (dB), typically the frequency at which the gain is −3 dB (70.7% of maximum). Figure 3-7 shows frequency response

[6]The reader should be aware of the following, often confusing, terminology: the high frequency filter setting is sometimes referred to as the low pass filter setting, i.e., it passes frequencies below it; the high pass filter setting determines the lower limit of the bandpass, i.e., it passes frequencies above it.

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curves for an a.c. amplifier suitable for AEP recording. Reference to the frequency response curve for his particular amplifier tells the AEP investigator what filter settings are required to achieve a flat bandpass over the approximately 1–100 Hz frequency range of AEP components. It is apparent that with the amplifier specified in Fig. 3-7, flatness cannot be achieved below approximately 0.5 Hz. To record accurately voltage fluctuations below this level, a d.c. amplifier and nonpolarizable electrodes are required.

It is also important to remember that the rolloff rate varies considerably among amplifiers and that there is no fixed relationship between the specified one-half amplitude or −3 dB point and the rolloff curve. For example, comparing two amplifiers commonly used for AEP recording, at a low frequency setting of 0.3 Hz, the frequency response is flat to approximately 1.0 Hz for one amplifier and 2.5 Hz on the other; at a setting of 1.0 Hz the flat limits are 5 Hz and 10 Hz. Some manufacturers do not furnish frequency response curves but give only the half amplitude or −3 dB point settings. With these, the user must determine his own frequency response curves. In any case, the careful investigator will verify the curves for his equipment, initially to determine that new equipment is operating within specifications, subsequently on periodic checks, and if a circuit modification is made or a component replaced.

Determining a frequency response curve is not difficult. Using a variable oscillator covering the appropriate frequency range, check its output linearity over the range. This is best done on an oscilloscope.[7] If the oscillator output voltage is not flat at different frequencies, reset its output for each frequency used. Voltage divide the oscillator output to within the minimum sensitivity of the amplifier. A frequency response curve is determined by plotting the gain at the amplifier output as a function of frequency for a fixed input and fixed gain setting. A frequency response curve should be determined for typical gains and all filter settings likely to be used in the experiment. Distortion of waveform and phase shift may be checked at the same time by comparing input and output signals on a dual channel oscilloscope.

One might conclude from this discussion that the safest procedure is to record from d.c. to some high frequency setting above any possible neural response. The safest perhaps, but in practice not the best. Direct current recording, besides requiring nonpolarizable electrodes, has the disadvantage

[7] Alternating current voltmeters may be used for calibration purposes. However, one must check their frequency response and most of them are not accurate at frequencies below 10 Hz. Also, they read in root-mean-square (rms) which is 70.7% of the base-to-peak value of an a.c. signal. Thus, 1 Volt rms equals 2.8 V peak to peak. Serious calibration errors result from forgetting this fact and, for example, reading input values in rms on a meter and output values base-to-peak or peak to peak on an oscilloscope.

that several kinds of artifacts, such as slow drifts due to changing electrode impedances or very slow potentials such as from body movements due to respiration, are passed by the d.c. amplifier but blocked by the capacitative coupling of the a.c. amplifier. The slow drifts must be continuously compensated by manual adjustment of balance potentiometers, a nuisance proportional to the number of channels being used, and the artifacts generally deteriorate the signal-to-noise ratio. Opening the high frequency filters beyond what is needed permits considerably more myogenic and electronic "noise" to be recorded than is necessary, which further deteriorates the signal-to-noise ratio. The best filter settings are those which eliminate the maximum spurious potentials without altering the waveform of the AEP. The best way to determine such settings is empirically. This is especially easy if multichannel recording is available. Figure 3-8 shows the effect of different high and low frequency settings on the SER using the amplifiers whose frequency response curves are shown in Fig. 3-7. In the left three columns the low frequency setting was held constant at 0.1 Hz and the high frequency half-amplitude settings were, top to bottom, 3000, 1000, 300, and 100 Hz. For the "moderate" and "noisy" records, broad-spectrum noise was added to the EEG at the amplifier input. A filter setting of 300 Hz which reduces amplitude only about 10% at 100 Hz (see Fig. 3-7) is the best setting for this amplifier. Above that there is no significant change in AEP waveform, but noise, if present, is added and can seriously obscure the response. A setting of 100 Hz, with which the rolloff begins at about 12 Hz, distorts the response, principally by amplitude reduction of both early and late components. However, if one had a very noisy subject (third column), one might use the 100 Hz setting, keeping in mind its effect on amplitude.

In the right column of Fig. 3-8, the high frequency setting is constant at 300 Hz, and the low frequency -50% amplitude settings were, top to bottom, 0.1, 0.3, 1.0, and 3.0 Hz. The most obvious change is that the decreasing low frequency response increasingly differentiates the positive peak of the vertex response, giving it a sharper appearance. The peak-to-peak amplitude of the vertex response is attenuated only by the 3.0-Hz setting where the peak latency also decreases. As expected, then, minimum distortion is at the 0.1 Hz setting; however, if special considerations demanded, a setting of 1.0 Hz *on these amplifiers* could be used without excessive distortion.

In addition to high and low frequency settings, some amplifiers have 60-Hz "notch" filters designed to eliminate power line interference from the records. Whatever their value for EEG recording, they should be used in AEP recording only as a last resort and with the knowledge that they will distort at least some components of the AEP. Figure 3-9 shows AEPs recorded simultaneously from the same electrode derivation through the same type of amplifiers using identical high and low filter settings. The only

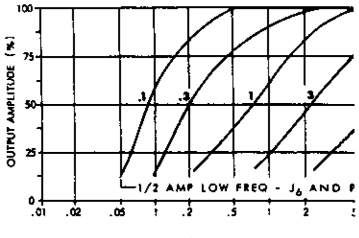

FIG. 3-7. Frequency response curves
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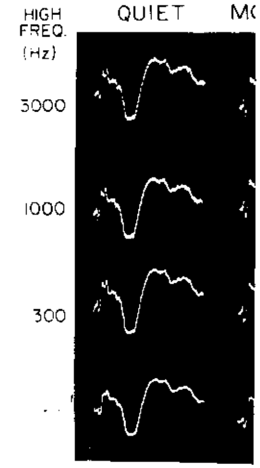

FIG. 3-8. Effects of high and low filt
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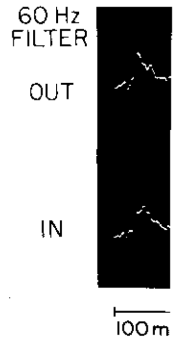

FIG. 3-9. SER recorded without (top
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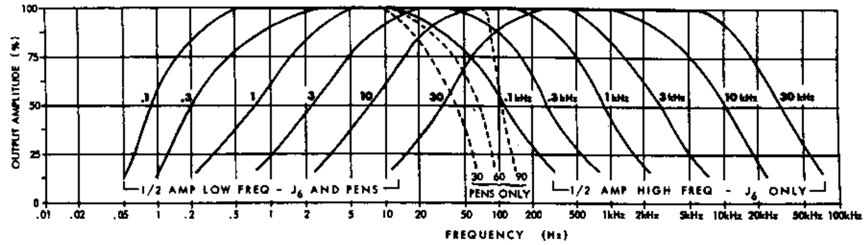

FIG. 3-7. Frequency response curves for high and low frequency filter settings for a Grass Model 7P511 EEG amplifier. Note that a filter setting indicates the point on its particular frequency response curve where the output amplitude is approximately 50% of the maximum in the flat part of the curve. (Courtesy Grass Instruments Co., Quincy, Mass.)

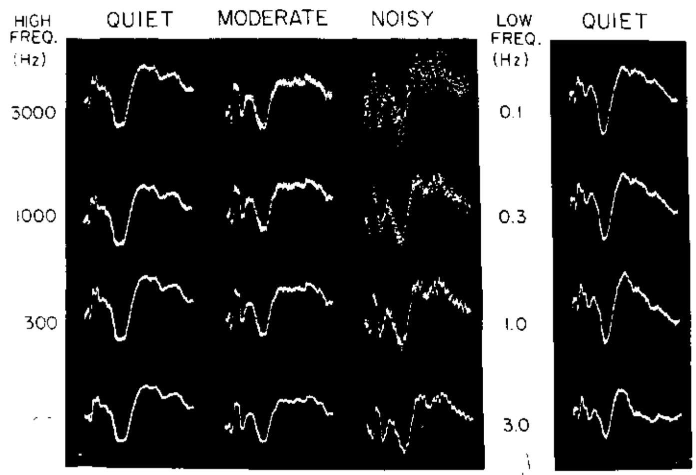

FIG. 3-8. Effects of high and low filter settings on SER to right median nerve shock recorded from P_3–A_1. Responses in each column were recorded simultaneously. Additional explanation in text.

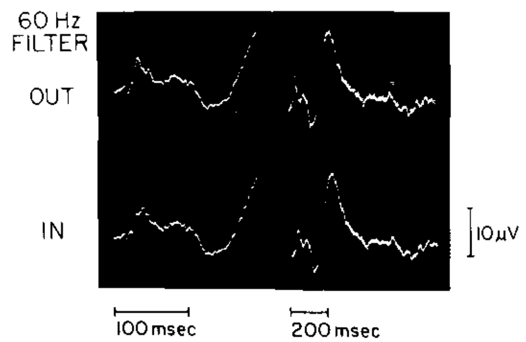

FIG. 3-9. SER recorded without (top row) and with (bottom row) 60-Hz "notch" filter. Derivation P_3–A_1; stimulus right median nerve shock.

difference between responses was that the 60-Hz filter was not used in the top and was used in the bottom records. The distortion of the early components compared in the left column is obvious; later, lower frequency components are unaffected.

The gain controls of an amplifier usually consist of a continuously variable control or a step attenuator, or preferably both. The gain is determined empirically by applying a known signal to the input, monitoring the output, and adjusting the gain controls to achieve the desired factor. It is imperative that the calibrating signal be within the flat frequency range of the amplifier when the filters are set as they will be during the experiment. If this seems like pointing out the obvious, I have known it to be overlooked. For example, a commonly used calibrator has a 1 kHz sine wave output. A commonly used differential amplifier has a high frequency filter setting of 1 kHz which was the setting to be used in the experiment. Calibration was done at this setting. But on this amplifier, 1 kHz indicated the -3 dB point. The calibration signal was thus being attenuated to 70.7% relative to lower frequencies. When gain was adjusted to 10,000 at 1 kHz, gains at lower frequencies were larger than specified. Opening the filter to the next higher setting during calibration, which brought the calibration signal into the flat gain range of the amplifier, then resetting it to 1 kHz during the experiment, solved the problem.

E. Common-Mode Rejection

In addition to the potentials resulting from neural activity, there are a variety of nonneural biological, and nonbiological potentials which occur between electrodes and between each electrode and ground. These potentials constitute "noise" with reference to potentials we wish to record. Nonneural biological potentials arise predominantly from muscle activity and eye movements. Nonbiological potentials are most commonly produced by electromagnetic or electrostatic induction from power lines (60-Hz interference) or electrical equipment (motors, relays). These artifactual potentials will be further discussed in Section VII. Fortunately, artifacts and interference signals are usually common to electrode pairs, and amplifier circuitry has been developed which discriminates against such "common-mode" or "in-phase" signals but not against signals which are out-of-phase, or "antiphase."

An historical perspective is the best way to understand the development and operation of the differential amplifier from the early, simple "push-pull" input circuit through the many subsequent improvements. According to Geddes and Baker (1968), the development was fostered by dual needs. First, there was a need for isolated inputs permitting the recording of true potential differences between independent electrode pairs. With single-ended

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amplifiers having a common power supply, the "second input" was the ground reference which in effect behaved like a common electrode. The second factor was the need to improve the signal-to-noise ratio by rejecting interference, especially from power lines.

The basic input circuit of the differential amplifier is the so-called "push-pull" design. This is essentially two single-ended amplifiers connected back-to-back symmetrically with reference to ground. After one or more amplification stages, the outputs of the two parallel amplifiers are brought together and the output is the potential difference between them at the common point. If an antiphase signal is applied to the two inputs, to the extent that these inputs are equal and opposite, i.e., 180° out of phase, equal and opposite amplification will occur in the two parallel amplifiers (the "push-pull" effect) and the potential difference between them at the common point will be twice that which would have been achieved by a single amplifier alone. Any in-phase potentials in the two amplifiers, whether they occur at the input or within the amplifier itself (e.g., from a common power supply, changes in ground potentials, etc.) will be amplified equally in the same direction and there will be no potential difference between them at the common point. As a result of this circuit, the two inputs are isolated from ground in that their potential difference from ground does not affect output; only potential differences between them are amplified. Referring to the discussion of monopolar and bipolar recording in Section IV, it is because only differences in potential between two electrodes are amplified that knowledge of the evoked activity occurring at both electrodes is critical to the interpretation of AEP records.

Push-pull circuitry made practical simultaneous recording from multiple electrode pairs and provided improved signal-to-noise ratios. There were still two problems, however. First, the efficacy of the circuit in cancelling in-phase signal is a function of the equality or "balance" in the gains of the parallel amplifiers. Circuits designed to approximate this equality are called balanced amplifiers. However, complete equality is not achievable and small imbalances significantly lessen in-phase rejection. Second, push-pull rejection works only if the in-phase interference is smaller than the antiphase signal. Otherwise, interference may cause serious distortion or "block" the amplifier before adequate signal amplification is achieved. It is possible for 60-Hz interference to exceed the signal by an order of 100,000 times (Geddes & Baker, 1968). Further modifications were devised to provide negative feedback for in-phase signals while leaving antiphase signals relatively unaffected; these are called discriminating or discriminative amplifiers. However, the term differential amplifier is the inclusive term used today to describe the dual input, in-phase signal-rejecting amplifier.

The "common-mode rejection ratio" (CMRR) expresses the capability of a differential amplifier to reject in-phase signals while amplifying antiphase signals. It is usually expressed as a ratio of the in-phase voltage to the antiphase voltage which must be applied to the input to produce the same output, or in decibels of attenuation of the in-phase signal voltage where 20 dB represents a factor of 10. Thus, a rejection ratio of 40 dB means that the common-mode signal voltage is reduced by a factor of 100 relative to the in-phase signal voltage.

Some manufacturers include a "differential balance adjustment" on their amplifiers. Instructions for setting the balance are generally provided. In general, one applies an in-phase signal, usually a 60-Hz sine wave since power lines are a maximum source of interference, to both inputs, displays the output on an oscilloscope and sets the balance adjustment for maximum cancellation. The importance of this adjustment is indicated by the fact that one commonly used amplifier has an optional balance adjustment. The CMRR without it is specified at a minimum of 1600:1 and with it, properly set, a minimum of 25,000:1. Common-mode rejection is one of the most important specifications in selecting a differential amplifier. The higher the rejection, the greater the amount of artifact and interference which can be permitted in the environment and still obtain good AEP recordings. Modern technology has produced differential amplifiers appropriate for AEP research which have CMRRs of up to 100,000:1 (100 dB).

F. Output Impedance and d.c. Level

To transfer signal voltage from one device to another, e.g., from an amplifier to a tape recorder, the output impedance of the amplifier should be low relative to the input impedance of the tape recorder. Otherwise, the input impedance of the recorder may shunt part of the amplifiers's output to ground, or in other words, load its output. If shielded cables are used to connect the devices, capacitative coupling also may shunt the signal in a high impedance cable. A low impedance output minimizes this capacitative loading. Low impedance is typically achieved by the use of a cathode follower (emitter-follower with transistors) circuit in which the potential of the cathode referenced to ground follows that of the grid. The output voltage is taken across the cathode resistor. It is necessary to compensate for the cathode bias voltage which would otherwise appear at the output. This is done by biasing the grid so that current flow through, and resulting voltage drop across, the cathode resistor is zero when there is no amplifier input. The grid bias is usually made adjustable by the use of a variable resistor. With amplifier inputs grounded, the grid bias resistor is adjusted to zero the d.c. level of the output. Most commercial instruments used in

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VI

A. Somatic Stimulation

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AEP recording are designed with high impedance inputs and low impedance outputs so that interfacing between system components is usually not a problem. One must be alert to the possibility, however. It may occur, for example, if one is connecting an amplifier output to an averager and tape recorder input simultaneously. The two inputs are in parallel with the amplifier output; thus they form a voltage divider circuit to ground. Both inputs may be "high impedance" with respect to the amplifier output, but there may be an appreciable difference between them. The lower impedance instrument may load the higher impedance instrument. "Loading" can be checked quite simply by monitoring the amplifier output of a calibration signal while plugging into the inputs of one or more instruments. There should be no diminution in the signal. If there is, interfacing or "mixing" amplifiers may be required.

VI. Stimulation

A. Somatic Stimulation

The most common method of evoking a somatosensory evoked response (SER) is to activate a peripheral sensory nerve by "percutaneous electrical depolarization," otherwise known as a shock through the skin. The most commonly used nerves are the median and ulnar at the wrist and the peroneal nerve in the leg. The same silver disks used for scalp recording serve well as stimulating electrodes using the same electrolytic substances to ensure good contact. Pastes or creams are preferable to jellies because they are less likely to ooze between the electrodes, cause a shunt, and lower effective stimulus intensity. The placement of the cathode as immediately as possible over the nerve is extremely important for effective stimulation. Placement of the anode is less critical; typical placment is approximately 2 cm distal to the cathode or off to one side with respect to the nerve. If the anode is too close to the nerve, anodal hyperpolarization may occur. After rubbing the skin with acetone or alcohol-moistened gauze to reduce skin resistance, the electrodes are attached with adhesive tape or collodion. Taking as an example stimulation of median nerve at the wrist, the procedure is as follows. The median nerve lies approximately between the flexor carpi radialis and palmaris longus tendons. These tendons are easily visualized if the subject makes a fist, palmar flexes his wrist, and resists as the experimenter tries to straighten the wrist. This brings the two tendons into prominence and the cathode is located between them slightly proximal from the wrist crease. The anode can be placed about 2 cm lateral. However, we have been achieving lower, more stable thresholds using an infant limb EKG electrode on the back of the wrist for an anode. The rubber strap holding it is arranged to pass over the cathode which holds the cathode tighter against the wrist, making stimulation more effective. Electrodes can be placed over most other nerves on the basis of anatomical landmarks. For locating a given nerve for the first time, for nerves whose precise location varies in different people, or for nerves which are not associated with obvious anatomic landmarks, a small, battery-operated, portable nerve finder (6) is a useful device.

Electrode placement should be verified empirically by asking the subject where sensation is localized. This requires knowledge of the innervation of the nerve being stimulated. For example, with median nerve stimulation at moderate suprathreshold intensities, the subject should feel a "tap" at the wrist under the cathode and a tingling sensation in the thumb, first, and second fingers and the palm below these fingers. If sensation is only in the wrist, either the placement is bad or anodal current is accidentally being applied.

Stimulation is usually a monophasic square wave pulse. Most stimulators can supply a relatively constant output if stimulating electrode impedance is not too high and does not vary greatly. If these two conditions are not met, electrode impedance changes can cause significant fluctuations in effective stimulus intensity. It is generally accepted that current rather than voltage is the relevant parameter for nerve stimulation (Becker, Peacock, Heath, & Mickle, 1961). Since interelectrode impedances are not stable, devices which maintain current at a constant level (independent within limits) of electrode impedance changes have been developed.[8] These units have output capabilities up to about 10 mA at typical stimulating electrode impedances. When selecting a stimulator, one should consider that constant current maximum output varies inversely with electrode impedance. A 10 mA output is adequate for most AEP experiments but not for purposes such as determination of intensity functions or in patients with sensory deficit due to central or peripheral neuropathology. A circuit for a constant current stimulator with output capabilities of 25–30 mA has been published by Allison, Goff, and Brey (1967). In this stimulator the output is the plate current of a pentode which has the inherent property of being virtually independent of changes in load impedances. Regulation within 5% is obtained for up to 25 mA for skin impedances below approximately 20 kΩ. Skin impedance for short duration pulses is considerably less than skin resistance because of parallel capacitance (Montague & Coles, 1966) which shunts skin resistance. Allison *et al.* (1967) found interelectrode impedance to be on the order of 100 times less than resistance. Thus resistance variations will have

[8]e.g., Grass Instruments Co. Model CCU 1 constant current unit; American Electronic Laboratories, Inc. Model 106 constant current regulator; and several others.

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relatively little effect in changing impedance. Schwartz, Emde, and Shagass (1964) compared SER intensity functions for a constant voltage stimulator to a constant current circuit very similar to that of Allison *et al.* (1967). They concluded that the constancy of the stimulator output was more important than whether the scale was in volts or milliamperes, and that the type of stimulator used made little difference for typical SER recording. They suggested that power might be the relevant stimulus parameter but this idea has not been tested.

The output of a shock stimulator must always be isolated from ground! The importance of this for subject safety and minimization of stimulus artifact cannot be overemphasized. Stimulus artifact occurs when stimulus current enters the amplifier. The magnitude of this current pulse is generally many times greater than the AEP signal and may block the amplifier. Amplifier recovery can take 50 msec or more and this will introduce serious distortion into the early portions of the AEP record. The problem is aggravated by response averaging since the shock artifact and any distortion it produces will be averaged along with a response. The most common "sneak paths" by which shock artifact reaches the amplifier are through a common ground, deliberate or accidental, and by means of conduction through the skin from stimulus to recording electrodes. The common ground path is defeated by isolating the stimulus source from ground. This is done by isolating the output *per se* from the main part of the stimulator, usually through an isolation transformer, or by isolating the entire stimulator as done by Allison *et al.* (1967). With either system, one must guard against accidentally compromising the isolation by, for example, using leads with grounded shielding running from the isolated output to the subject. Pulses have very high frequency components which lend themselves to capacitative shunting between leads and grounded shielding, especially with the high impedance circuit requisite for constant current stimulators. Capacitative coupling increases with lead length and to the extent that it occurs isolation from ground is compromised and shock artifact is likely.

Artifact radiation along skin can be minimized by placing a low resistance shunt to ground between the stimulating and recording electrodes, which "decouples" them. We have found that a 1-inch wide length of tinned copper, flexible "ground strap," or a strap of conductive rubber (7) liberally smeared with electrode jelly or paste, and wrapped around the limb proximal to the stimulating electrodes provides effective decoupling. The metal strap is held in place by an elastic band commonly used with EKG electrodes. The rubber strap is easier to clean and fastens with a buckle which is more convenient and facilitates tension adjustments. The straps are bound in gauze to reduce electrolyte drying and protect clothes. Grounding the subjects in this manner also reduces 60-Hz interference (see Section VII). Under conditions where it is impractical to wrap the limb with a ground strap, an EKG plate electrode will provide reasonable artifact reduction. Proximity between stimulating and recording leads is another important factor in determining shock artifact interference.

Isolation from ground helps to protect the subject from the effects of accidental excessive shock by limiting the current path between the closely spaced electrodes. Without such isolation, should equipment malfunction combine with unintentional grounding of the subject such that the current path includes the chest area, relatively small currents could produce cardiac and respiratory arrest. The ground placed on the subject provides additional safety since it is normally placed on the limb being stimulated and thus should isolation failure combine with stimulator malfunction, it provides a path to ground which avoids the chest region. As a final safety precaution, the output of all electrical stimulators used for human research should be fused. Note that output fusing is not the same as the 110 V a.c. line fuse which commonly protects instruments from shorts. These do not necessarily protect the subject. Allison *et al.* (1967) fused their output with 10 mA fast-acting fuses which they found would "blow" when subjected to a single 1.0 msec pulse of about 25 mA.

Stimulators should be calibrated empirically through the isolation units. To maintain isolation from ground, an oscilloscope with a differential input is required. The stimulator pulse is displayed on the oscilloscope and voltage is read directly across a 1% resistor in the range of typical electrode impedance (10 kΩ) in parallel with the oscilloscope input. To calibrate a constant current device, current is calculated from Ohm's law, i.e., by dividing the voltage displayed on the oscilloscope by the value of the load resistor. Again, the load resistor should be in the same range as typical electrode impedances. A calibration curve is constructed by plotting the voltage or current values as a function of stimulator setting. These calibration curves should be checked on a regular schedule and always after replacement of any component of the stimulator system.

Determining the effective stimulus intensity, as distinguished from the physical voltage or current, for the purposes of equating intensity within and across subjects and sessions is a considerable problem with electrical somatic stimulation. Specifying intensity in "sensation levels" (a given intensity above absolute threshold) as is commonly done for auditory stimulation can be misleading. The absolute threshold will be based on cutaneous sensation immediately under the cathode and the relationship of this to depolarization of the nerve trunk is uncertain. The absolute threshold for sensation in the innervation area of the nerve would seem a better index but has not been used. Furthermore, neither of these indices is likely to be useful in a patient with sensory deficit. When using a "mixed" nerve, that

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is, one with both motor and sensory fibers, the threshold for activation of the motor fibers producing a twitch in the muscles innervated by the nerve seems to be the best objective standard of intensity. Except in cases of peripheral neuropathy, it is usable in sensory deficited, aphasic, or comatose patients as well as normal subjects. Median nerve stimulation produces a palmar twitch of the thumb. Taking the thumb twitch as a standard of effective median nerve stimulation, it is easily demonstrated that changes in wrist position shift the electrode-nerve relationship and change effective intensity. The intensity which produces a twitch with a hand palm up may not if the hand is rotated palm down; similar changes occur between the dorsiflexed, unflexed, and palmar flexed wrist. For this reason, a hand rest should be used whenever possible to keep the subject's wrist in a constant, preferably slightly dorsiflexed, position. Thumb twitch threshold should be determined in this position and the subject instructed not to change the position during the session. If an arm rest is not practical, some means of maintaining a constant wrist position should be used. For most SER recording, we typically use a stimulus intensity of 3 mA above twitch threshold; in a normal subject this is usually an absolute value of 4–6 mA although values of 10 mA or better are occasionally required.

Typical durations for shock stimulation range from 100 μsec to 1 msec. The well known strength-duration relationship means that higher current levels are required at shorter durations for equally effective stimulation. Longer durations at higher current levels may increase stimulus artifact and may produce an unpleasant burning aftersensation. We use a 500 μsec duration and this is rarely painful even at 25 mA. Poor electrode contact with the skin which elevates current density per unit area may cause pain even at short durations and a relatively low current level. Reapplication of the electrode to improve skin contact should correct the problem.

This discussion has dealt mostly with electrical median nerve stimulation. It is the most frequent choice for SER research because of the ease with which one can locate the nerve, place stimulating and grounding electrodes, objectively determine the effect of stimulus intensity, and maintain a reasonably constant nerve-electrode relationship. Other stimulation sites and non-electrical stimulation have been used to evoke SERs. Responses to electrical stimulation of the finger have been compared to electrical median nerve stimulation (Calmes & Cracco, 1971; Goff *et al.*, 1962). The differences found can be attributed to lower effective intensity stimulation of the finger resulting from the activation of fewer nerve fibers. SERs to vibratory (Desmedt, Debecker & Manil, 1965; Ehrenberger, Finkenzeller, Keidel & Plattig, 1966; Franzén & Offenloch, 1969) and punctiform tactile stimulation (Meyjes, 1969; Shevrin & Rennick, 1967) have been reported. Meyjes (1969) compared the SER to an electrical stimulation of the finger, and the blunt and sharp side of a "neurological pin" in 19 subjects. The waveforms of the three responses compared very favorably; there were slight differences in latencies, with electrical stimulation being the shortest. Meyjes also listed the disadvantages of mechanical stimulation as noise concurrent with stimulus application, inconvenience in changing the site of stimulation, and the possibility that application of large numbers of stimuli may injure the skin. To these, I would add the expectation that most electromechanical drivers would involve an inductive voltage which is a potential source of stimulus artifact.

B. Auditory Stimulation

The description, measurement, and control of the kinds of sound used to stimulate AERs are discussed by Hirsh (1966) and the parameters of auditory stimuli are discussed by Licklider (1951). It is therefore appropriate to present here only a brief overview, including certain problems peculiar to AER recording.

The most commonly used AER evoking stimulus is a click which is a very brief transient change in sound pressure. The click is usually generated by a monophasic square wave electrical pulse to an earphone. The maximum pulse duration which produces a "clean" click is about 1 msec. Clicks longer than this have a "ragged" sound or may be perceived as two clicks with a silent interval to the extent that the ear can resolve the rise and fall of the pulse. They are complex, difficult to quantify, and normally avoided for AER work. For stimuli of longer duration, pure tones, complex tones, or noise are possible sources. A pure tone is one whose sound pressure changes as a function of time have a sine waveform. They are generated by audio-frequency range oscillators. A useful instrument for generating pulses or pure tones is the voltage-controlled signal generator (8). This instrument provides sine, triangular, or square wave signals, the frequency of which may be controlled by a voltage input. It is especially useful for rapid changes to predetermined frequencies controlled manually by a fixed step voltage divider or remotely by the digital-to-analog output of a computer controlling stimulus presentation. Complex tones as such are not usually used to evoke AERs. They are sounds with a periodically repeated waveform which is a mixture of two or more sine wave components. The resulting difficulty of specification and quantification makes them less desirable than pure tones as stimuli. Noise, in the context of a stimulus, is a sound comprised of multiple, aperiodic, random-frequency components. The term white noise is sometimes used to refer to noise having a wide frequency spectrum. Electronic noise generators are commercially available, some of which (9) have an input for externally generated signals which can be "mixed" with, i.e., superimposed upon, the noise. These are useful for masking experiments.

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Tones and noise are continuous signals and must be converted to discrete stimuli to evoke AERs. In other words, they must be converted to tone or noise "bursts" with onset and offset. Tone bursts have the advantage of frequency control if discriminative stimuli are desired. Tone bursts as short as 10 msec can be discriminated on the basis of frequency even though their short duration makes them sound more like a ragged click.

A major problem with tone or noise bursts is turning them on or off without generating a switching transient, that is, an onset or offset which is so rapid that it creates a click when applied to the electroacoustic transducer (earphone or loudspeaker) which converts the electrical energy to sound pressure. With any signal in which the voltage is continuously varying with no fixed temporal relationship to its connection or disconnection from the transducer, it is probable that at the instant of onset or offset, the voltage will not be zero. Thus, if an ordinary mechanical switch is used, there will be an instantaneous change in potential applied to the transducer, thus producing a click. This contaminates the stimulus if one is investigating the AER to nonclick stimuli. The transient can be avoided by turning the signal on or off gradually and instruments called electronic switches or switching amplifiers are commercially available for the purpose (10). Mechanical and photoelectric switching devices are usually cheaper but have relatively prolonged rise and fall times, that is, time from onset to full signal amplitude and maximum signal back to zero. An electronic switch can provide a rise and fall time of as little as 2.5 msec without an audible click. For short duration bursts, such rapid rise and fall times are necessary. Commercial electronic switches are available with gain controls and dual inputs wired so that when one comes on the other goes off, thus allowing rapid shifts from one signal to another. These switches are usually gated, that is, turned on and off by external triggering so that the duration of the stimulus is determined by the width of the gate pulse.

There is increasing interest in AERs evoked by speech sounds. We have recently found hemisphere-specific differences in evoked potentials between tasks which require identification of linguistic *versus* nonlinguistic acoustic parameters of the same computer-synthesized sound (Wood, Goff, & Day, 1971). Problems with noncomputer-synthesized speech sounds are lack of control over parameters and difficulty in synchronizing averaging devices.

Whatever the nature of the auditory stimulus and however it is generated, it must ultimately be converted from electrical to sound wave energy by an earphone or speaker. Speakers are used for so-called "free-field" stimulation; they are limited to binaural stimulation, and effective intensity and binaural phase relationships vary with the position of the subject's head with respect to the speaker. Earphones are therefore generally preferred. Circumaural earphones provide a significant degree of attenuation of extraneous sound which is especially important when the subject is not inside a sound attenuating chamber. However, they can present problems for AER recording. First, they are usually connected by a headband and it can be difficult to place the headband or the circumaural cushion so as not to rest on a scalp electrode and cause discomfort. Second and most important, the driver units for this type of earphone typically have relatively large coils and we have found that they can introduce serious artifact into the recording in proportion to the duration of the stimulus. Bursts of tone, noise, or speech will be superimposed on the AER due to electromagnetic induction of currents in recording leads by the earphone coil. Miniature earphones of the type used in hearing aids (11) have much smaller coils and do not introduce artifact. These are inserted into the ear canal and taped in place if necessary. The discomfort of a headband or ear cushions pressing on electrodes is also eliminated. However, if circumaural sound attenuation is desirable and electrodes can be placed to avoid the headband and cushion pressure, earmuffs of the type used near jet aircraft worn over the miniature earphone provide very efficient sound attenuation.

The calibration of AER stimulating equipment varies with the type of stimulus used. A problem common to all types, however, is describing the transformation from the electrical energy of the generator to the sound pressure energy output of the transducer. First of all, impedance matching is necessary for the maximum transfer of power[9] from generator to transducer. Impedance mismatches seriously reduce power transfer and may require the interpolation of impedance matching transformers or interfacing amplifiers. Even with matched impedances there will be some power loss. As a result, measuring the voltage at the input to the transducer says little about the stimulus energy reaching the ear. As with any system, the best way to calibrate is through the entire system, transducer included. Various instruments and methods for this purpose are discussed by Licklider (1951) and Hirsh (1966). The amplitude of transient signals always presents a more difficult quantification problem than a continuous signal since their duration is usually too brief for the measuring instrument to respond and a valid reading to be taken. Clicks therefore require for calibration an impact noise analyzer (12) which samples and stores peak value, maximum instantaneous level, and time duration of impact sound. Impact noise analyzers must be used in conjunction with sound level meters of the type used to measure continuous signals (13).

Frequency of a pure tone may be checked in various ways as described by Hirsh (1966). Perhaps the easiest way is to use an events per unit time

[9] Optimal transfer of power requires impedance matching; optimal transfer of voltage requires a low impedance output to a high impedance input.

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(EPUT) meter (14). An EPUT meter has several other functions and we have found it valuable as a general laboratory instrument.

Unfortunately, even these methods do not precisely quantify the sound pressure actually impinging on the ear drum, and if they did, would not take into consideration individual differences in auditory sensitivity which varies as a function of frequency, age, pathology, etc. Therefore, a commonly used practical procedure for equating auditory stimulus intensity between ears, sessions, and subjects is to specify in terms of sensation levels (SL). Sensation level is the amount of energy, specified in decibels, above the minimum energy a subject can hear, or in other words, above the subject's absolute threshold. The threshold is determined by standard psychophysical techniques, usually the method of limits, in which the intensity is gradually increased and decreased until the subject reliably reports or ceases to report hearing it. The average of one or more ascending and descending series is taken as the absolute threshold. The stimulus is then increased to typically 60–70 db above this level or in other words, 60–70 db SL. The simplest way to determine absolute thresholds and specify sensation levels is to interpolate attenuators (15) between signal generators and transducers. These attenuators sometimes also solve impedance matching problems. They usually have 10 db and 1 db step controls; thus the absolute threshold and sensation levels may be read directly from the attenuator setting, assuming it is accurate. A complete research report will still measure and specify the physical characteristics of the stimulation used.

Auditory stimulation presents no special problem with regard to the safety of the subject save one. That is guarding against the accidental presentation of excessive sound pressure levels which can produce pain and even permanent damage. For example, the oscillator output level of a 1000-Hz signal required to produce a 10-msec tone burst at 70 db SL may be very unpleasant or painful to the subject if accidentally switched in as a continuous signal. Furthermore, it may produce a (hopefully) transient hearing loss which affects the experimental results. Again, a 70-db SL click presented at a low repetition rate is not uncomfortable. If the repetition rate is accidentally raised $\times 10$, $\times 100$, or $\times 1000$, which are common step controls on some instruments, the result is most unpleasant. In general, the earphones should never be placed on the subject until all equipment is checked out and known to be working properly. If "trouble-shooting" is required during the session, the earphones should be disconnected.

C. *Visual Stimulation*

Several recent articles describe in extensive detail the generation, control, calibration, and specification of visual stimuli (Boynton, 1966; Riggs, 1965).

Graham (1965) presents some basic terms, methods, and data of importance to the VER investigator and Perry and Childers (1969) discuss VER stimulation variables. The reader is referred to these sources and only a few general comments are presented here.

In terms of physical control, the best way to present visual stimulation is by Maxwellian view. By this method, the light is focused to a point on the cornea causing all the light to enter the eye regardless of changes in pupillary constriction. The light beam expands beyond the focal point and stimulates a section of the retina according to the visual angle determined by the focal length of the lens. Maxwellian view system construction is discussed by LeGrand (1968) and Riggs (1965). The problems with Maxwellian view stimulation for VER work are: first, the head must be held rigid. This is typically done in non-VER experiments by a "biting board," an impression of the subject's teeth which he bites into to hold his head rigid. We quickly found, as one would expect, that the muscle potentials produced by biting made VER recording virtually impossible from any electrode over head muscles. Substituting a chin and forehead rest allows recording from some subjects. Second, regardless of the head-holder, the subject must voluntarily maintain occular fixation for the prolonged periods of repeated stimulation required for VER recording. This kind of highly motivated cooperation is usually found only in subjects with a vested interest in the success of the experiment, such as co-workers and relatives. Thus, Maxwellian view stimulation is generally not feasible for many subjects and especially not for patients.

The easiest method of VER evocation is with stroboscopic photostimulators (16) but control over the light actually entering the eye is poor. Control of pupillary dilation by drug administration or the use of an artificial pupil helps. Occular fixation is still important though less critical than with the Maxwellian view. A patterned stimulus usually evokes a better-developed evoked response. Some investigators are experimenting with the use of fiber optic "light pipes" but to my knowledge they have been used only in animals (Spehlmann & Smathers, 1968). Glow modulator tubes have the advantage that they can be triggered or modulated by a signal such as a pulse or sine wave, but their energy output is small and their spectral characteristics change with modulation. A good, practical method for general application with unsophisticated subjects and patients has been developed by Dustman and Beck (1965). A white, plastic sphere of approximately 28 inches (70 cm) in diameter is placed approximately 16 inches (40 cm) from the subject's face. It is either transilluminated or reflectively illuminated by a stroboscope. If care is taken to illuminate the sphere homogeneously, changes in effect of stimulus intensity due to changes in occular fixation are minimized as long as gross head movements, which can easily be observed by the experimenter, are not permitted.

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D. Odor Stimulation

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E. Taste Stimulation

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F. Stimulus Repetition Rate

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The main artifact problems peculiar to visual stimulation are sounds associated with stroboscopic discharge and inductive currents from the discharge or trigger pulses. If possible, having the light source outside a sound-attenuating recording chamber and beaming it in through a window with double glass to preserve sound attenuation is desirable. This also eliminates heat problems in the recording chamber from light sources and power supplies. If this is not possible, the strobe light itself may require a soundproof housing. Possible contamination from sound and electroinductive artifacts may be assessed by blocking the light and response averaging with all other conditions held constant; time-locked potentials should not be seen. Proper separation of stimulating and recording leads should eliminate inductive artifacts.

D. *Odor Stimulation*

Apparatus for obtaining evoked responses to odor stimulation have been reported by Finkenzeller (1966) and Allison and Goff (1967) who found the response to consist mainly of a positive wave peaking at 450–550 msec. Although initial evidence suggested that the response was olfactory, Smith, Allison, Goff, and Principato (1971) concluded that the response was mediated by trigeminal nerves.

E. *Taste Stimulation*

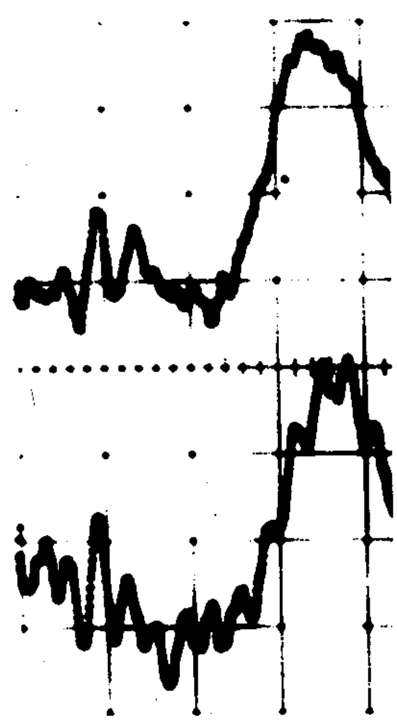
Summated cerebral evoked responses to taste solutions applied to the tongue have been reported by Funakoshi and Kawamura (1971).

F. *Stimulus Repetition Rate*

A consideration of great importance for AEP research is the rate at which stimuli are presented. It is well known that the response to a second or test stimulus (TS), is altered by the occurrence of a response to a preceding, or conditioning, stimulus (CS) (Allison, 1962; Bergamini & Bergamasco, 1967 and references cited therein; Davis, Mast, Yoshie & Zerlin, 1966; Gjerdingen & Tomsic, 1970; Rothman, Davis, & Hay, 1970). The alteration usually consists of a depression of the second response to a degree inversely proportional to the CS-TS interval. However, facilitation, or enhancement, of the response is reported for certain CS-TS intervals (e.g., Shagass & Schwartz, 1964). In the somatic system, Allison (1962) showed that the different components of the SER have different recovery function—in general the length of time for recovery is proportional to the component latency. The importance of interstimulus interval (ISI) for experimental results is illustrated by Beagley and Kellogg (1970) who found radical differences in the shape of AER intensity functions using a 1.25 sec versus a 20.0 sec ISI.

A minimum of 48 to 64 stimuli must be presented to obtain a reasonable AEP and three to six AEPs are needed to estimate the reliability of the response. Experimenters are therefore legitimately concerned about response variability introduced by changes due to habituation, drowsiness, or fatigue during the resulting long session. This has led in some cases to the use of stimulus repetition rates which are well within the "recovery cycle" of AEPs. Goff (1969) pointed out that all evidence indicates that alterations in evoked responses within and between modalities occur as a function of repetition rate and that they are differential between subjects and between AEP components. Generally, the later the component, the more susceptible it is to alteration as a function of repetition rate. Estimates of time required for "complete" recovery range from 3 to 4 sec in the somatic system (Allison, 1962) to as long as 10 sec in the auditory system (Davis *et al.*, 1966). Obviously a compromise is required between excessively long recording sessions and excessive response distortion. Around 3.0 sec ISI is appropriate for most purposes. If one is interested only in early components, shorter interstimulus intervals may be appropriate. For AER clinical audiometry, Davis and Niemoeller (1968) state that an interval of 1 sec gives the maximum vertex potential voltage per minute of sampling. Perhaps the empirical approach is the best. That is, compare a response evoked at a long ISI to responses evoked at shorter intervals. The shortest interval which does not produce serious distortion in the AEP components under investigation is the appropriate one.

A final caution about stimulus repetition rate peculiar to averaging is to be sure that the repetition rate is not a multiple of the period of 60 Hz, i.e., 16.66 msec. As will be discussed in Section VII, 60-Hz interference is one of the most common problems in AEP recording. A repetition rate which is a multiple of 16.66 msec will "phase-lock" the averaging to the 60 Hz and enhance the 60 Hz as well as the AEP. It is not a common problem, but it can happen. For example, an ISI rate of 1.5 sec is close to 1.66 sec; 3 sec is close to 3.32 sec, etc. If a stimulator is set inaccurately or out of calibration, an ISI which will phase-lock to 60 Hz can occur. Instrument malfunction can also be a cause, as a recent experience in our laboratory illustrates. During recording, we were puzzled by the appearance of 60 Hz in the average when none was discernible at the averager input. Changing stimulators although maintaining the same nominal ISI cured the trouble. Figure 3-10 illustrates the difference. The upper trace is a click-evoked AER recorded with a properly functioning stimulator at an ISI of 4 sec. The bottom trace was recorded under identical conditions but with a stimulator which proved



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VII. Recording Sys

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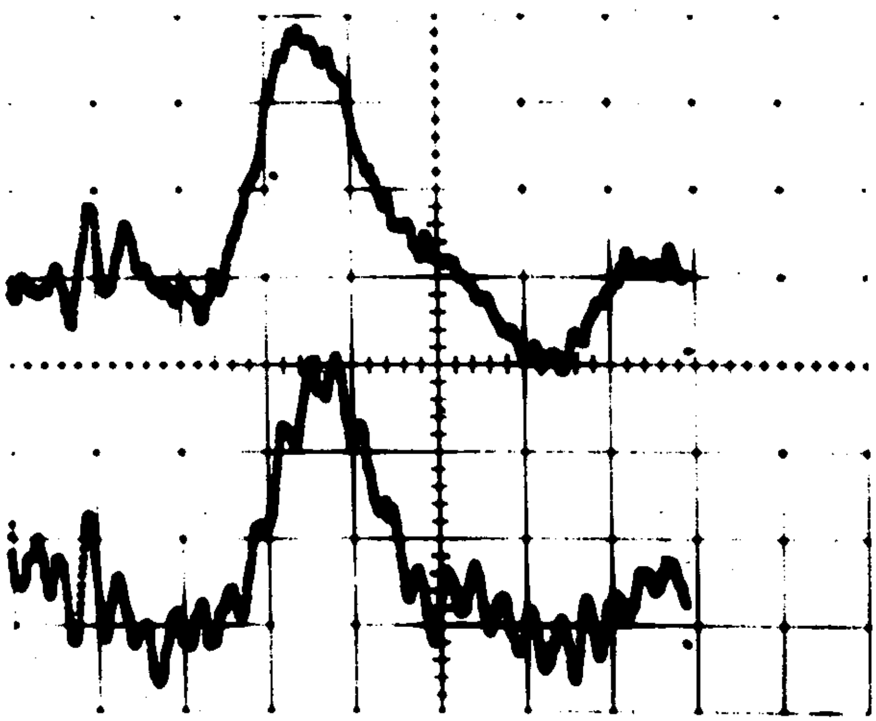

FIG. 3-10. Effect on an AEP of accidental phase-locking to 60-Hz of a nominal 4-sec interstimulus interval causing summation of the 60 Hz (bottom record) compared to recording under identical conditions but no 60-Hz phase-locking (top record).

to have 60-Hz ripple in its triggering circuit, causing the trigger to phase-lock to 60 Hz.

VII. Recording Systems, Artifacts, and Interference

The irreducible elements of an on-line AEP recording system are electrodes, amplifiers, a stimulator, an averaging device, and some shielded cable to connect them together. One can substitute a tape recorder for the averager and average responses off-line with access to a computer having appropriate input-output (IO) equipment. On the basis of experience, I consider off-line response averaging to be, in the general case, an undesirable method for AEP research because of lack of feedback of results, possible loss of data, and the fact that because we are working with "real-time" data, off-line averaging nearly doubles the experiment time unless technically difficult tape "time compression" is achieved. However, tape recording in conjunction with on-line response averaging is desirable in permitting re-analysis of data in different ways.

Though much valuable research has been done by AEP investigators equipped with little more than a basic system, such is not optimal. A complete AEP recording laboratory might be equipped approximately as follows. A sound-attenuating, radiofrequency shielded recording chamber (17) large enough to hold a bed or at least a reclining chair has the obvious advantage of providing a reproducibly homogeneous sound and light environment. Sound-baffled ventilation is necessary, and variable illumination control is desirable, for subject comfort. It is important that the subject be seated or lying comfortably so as to keep muscle tension in the head or neck region to a minimum to avoid the myogenic artifact potentials discussed in Section IV. Provision for auditory intercommunication by which the subject is always monitored is mandatory. Closed circuit television monitoring is highly desirable, especially with patients; it frequently reveals actions by subjects such as changes in wrist position (shock stimuli); dislocation of earphones (auditory stimuli); shifts in fixation, head position, eyes closing (visual stimuli); or other idiosyncrasies, not noticeable by other monitoring, which can affect the experimental results.

Multiple recording electrodes are most conveniently connected to the amplifiers by means of a multiple jack plug-in board through an electrode selector switch panel located outside the chamber. Monitoring of the EEG is best done after the final stage of amplification just prior to input to the averager. An oscilloscope is practical for monitoring up to four recording channels simultaneously. If multiple oscilloscope inputs are not available or if more than four channels are in use, a selector switch on the oscilloscope input facilitates monitoring. Obviously, oscilloscopic monitoring provides no permanent EEG record. A better system is provided by modern EEG machines whose amplifiers have filter settings appropriate for AEP recording and IRIG compatible (see Section V,B) output jacks which permit their output to be led directly to the input of most averaging devices and tape recorders. The multichannel EEG is simultaneously graphed along with stimulus and time markers, providing a permanent record from which one may refer back to such things as the amount of muscle activity or the state of the subject when a particular response is obtained.

We have found it advantageous to provide the subject with some feedback and control over the experiment. A small, preferably battery-powered, oscilloscope upon which the subject can observe his EEG greatly assists him in reducing muscle tension. He is instructed to minimize the "width"

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of the EEG trace by trial-and-error adjustment of jaw, neck, or torso position. A counter (18) indicating the number of stimuli presented is useful if the subject knows how many responses are required for a given summation. A subject with an urge to cough or sneeze, for example, can usually inhibit it if only a few stimuli remain. Subjects seem to endure experimental sessions better with this kind of feedback. Finally, a "panic button," with which the subject can interrupt the summations for some urgent need, makes him more comfortable and more relaxed. This is as easy as a switch which grounds a trigger pulse or sets a flag on a programmable computer. The "panic button" should also activate some kind of experimenter alerting device as an added safeguard for the subject. We have found that the sound attenuation of our recording chambers from the inside out is noticeably superior to the reverse. Auditory intercommunication systems sometimes fail and even if television monitoring is available, the experimenter's attention may be elsewhere.

The components of a system having been assembled and interconnected, the system should have provision for rapid calibration of system gain. The EEG amplifier gain calibrated as discussed in Section V,D is not necessarily equivalent to the gain of the entire averaging system upon which determination of AEP amplitudes is based. System gain must consider the effect on the signal of every component which affects the signal. For example, the inputs to analog-to-digital converters in most averagers and computers have input attenuators or "buffer" amplifiers. The attenuators may have several settings. The amplifiers usually have a nominal gain of unity, but will vary slightly. The most efficient and accurate method for system calibration is to put a known signal on the input of the EEG amplifier and read the output of the final system component, usually the averager. Some experimenters go further and summate or average the calibration signal, usually a square-wave pulse.

One of the most important activities of the experimenter before and during AEP recording will be the control of artifacts. In the context of AEPs, an artifact may be considered any electrical activity in the record which does not originate in the brain. Thus the EEG is not an artifact although it is sometimes heretically referred to as "noise" by the AEP purist. Artifacts are the investigator's constant companion because they may be introduced by the subject, by minor changes in equipment configurations or interconnections, or even by changes in electrical equipment external to the laboratory. Artifacts may be roughly dichotomized into those generated by the subject and those which are independent of the subject. The dichotomy is not complete since the subject sometimes serves as an antenna which conducts artifactual signals into the system.

Subject-generated artifacts which contaminate AEP recording, with the exception of those resulting from stimulus presentation discussed in Section VI, also interfere with EEG recording and are extensively discussed in that literature frequently with excellent illustrations (e.g., Cooper *et al.*, 1969; Dunn, 1967; Fuller, 1965; Mowery, 1962; Peters, 1967; Walter & Parr, 1963). The reader should refer to these sources.

Subject-independent sources of artifacts, frequently called interference, arise from a frighteningly large number of sources. An excellent discussion of interference sources and practical steps in their location and elimination is that of Wolbarsht (1964).

The most common source of interference is 60-Hz currents introduced into the system by inductive, capacitative, or resistive coupling from a.c. power lines. Stacy (1960) estimates that this is the source of 90% of instrumentation difficulties. This interference must be eliminated or at least minimized by adequate shielding and proper grounding to the point where it can be cancelled by the common mode rejection of a differential amplifier (see Section V, C). The principles of shielding and grounding are well explained by Stacy (1960), Thompson and Yarbrough (1967), and Wolbarsht (1964). The location and elimination of 60-Hz interference is an art rather than a science and it is not unusual to cure the difficulty without knowing exactly why, which renews faith in religion and invokes the credo "if it works, leave it alone." However, the following procedures have been successful in our laboratory.

Assume that a subject has been connected to the system, we are ready to record, and the monitor shows suspicious-looking continuous periodic activity either superimposed upon or totally obscuring the EEG. This will usually be 60-Hz interference but the first step is to verify that it is. It may appear as a simple sine wave, or as a complex sine wave due to the presence of harmonics. However, the fundamental period will be one peak approximately every 17 msec. On an oscilloscope sweeping at the rate of 50 msec per major division, this is three peaks per division. If an EEG machine is the monitor, it may have a 60-Hz "notch" filter and switching the filter in will identify the signal as 60 Hz if it diminishes or eliminates it. (This filter should not be used during AEP recording, see Section V,D.) Having obtained a visual display and verified the source as 60 Hz, the next questions are whether it is peculiar to one or more channels or common to all channels, and whether it is intrinsic or extrinsic to the system, in other words, is it on the subject or apparatus side of the EEG amplifier input. This is simply tested by shorting together the amplifier inputs at the electrode board. Shorting with the switching panel or by switching from "use" to "calibrate" on an EEG machine does not test for problems in the electrode board itself

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such as a loose input jack shorting to ground. If the 60 Hz is eliminated by amplifier input shorting, the system is "clean" and the trouble source is "pickup" from the recording leads on the subject. Check to see that the subject has a low resistance ground, preferably connected to the amplifier ground since grounding to some other point may cause a "ground loop" and introduce 60 Hz. Special grounding techniques for shock stimulation were discussed in Section VI, A. Otherwise, an EKG electrode on an arm or leg provides adequate grounding. Check recording electrode impedance with an impedance meter (resistance meters polarize electrodes, see Section III). An impedance of 10 kΩ or less is desirable. If the subject is in an unshielded environment, lower impedances may be required. If the 60 Hz is selective as to channel, interchange amplifiers to check for instrument malfunction. If the problem is channel but not amplifier selective, check electrode impedances, the cleanliness of the electrode plug-in pins, the soundness of the connection between pin and plug-in jack, and the integrity of the jack itself. Make sure the leads are cabled so that they follow the same path to the plug-in board. This is always important; if the path of two input leads to a differential amplifier are sufficiently separated, the phase angle of the pickup of the common source signal may differ sufficiently to compromise the common-mode rejection of the amplifier.

If the 60 Hz has appeared during the session, the ground or recording electrode electrolyte may have dried out and renewing it may be necessary. Sometimes electrolyte squirted under the recording or ground electrode by means of a syringe and blunt hypodermic needle will avoid reapplication of electrodes.

If electrodes and grounding are appropriate, and the subject is not in a shielded recording chamber, trial-and-error changes in his position with respect to 60-Hz sources such as the recording equipment itself, ceiling lights, electric cables in floor or ceiling, etc., may produce an orientation that will reduce the interference sufficiently to permit recording. If not, a shielded chamber, amplifiers with a higher common-mode rejection ratio, or moving to a different room may be required.

Even with the subject in a shielded chamber and appropriate electrode impedances and grounding, 60-Hz pickup may occur. This indicates that excessive 60 Hz is being led into the chamber. N. P. Thompson and Yarbrough (1967) discussed various ways this can occur. We have found that we can violate some of the general principles they discuss. For example, we run an a.c. line into the recording chamber for our TV camera, keeping it remote from the subject and tightly up against the metal ceiling of our chamber does not generate noticeable interference. However, any wire penetrating the shielding of the chamber is a potential source of interference. The offending source is best located by removing each possibility while constantly monitoring until the interference is eliminated. Pickup in the chamber can usually be demonstrated by the use of a "dummy subject," that is, by connecting two leads with a resistor between them to the amplifier input. We use at least 100 kΩ resistance to maximize pickup since if it is eliminated with this amount of "interelectrode impedance," we are quite sure of clean records at the lower values obtained with a real subject. The "dummy subject" is also an excellent way of checking out a new or modified recording system.

Returning to the test in which input leads were shorted together, assume that the 60-Hz interference was unaltered, indicating the problem is intrinsic to the recording system. If the 60 Hz is diminished but not eliminated by input shorting, one may have a dual problem in which case the intrinsic problem should be solved first. By far the most common source of 60-Hz interference intrinsic to the system is a "ground loop." This can occur when any of the elements of a system, including the subject, are connected to "ground" at two or more points. These points may have slightly different resistances to ground, permitting interference "pickup," resulting from the types of coupling mentioned above, to generate a potential difference between them. The circuit (loop) is completed through the ground. Because of the generally low resistances involved, the current flow may be appreciable and the resulting potentials can be amplified into the volt range by the high amplification used in AEP work.

Ideally, then, there should be only one connection to ground. This eliminates the possibility of a loop. A practical way to do this is to use "series" rather than "parallel" grounding. Series grounding means simply that the first component of the system, e.g., the recording chamber, is connected to the main ground bus, the next component, e.g., the amplifiers, is grounded to the chamber, the next component is grounded to the amplifiers, etc. Parallel grounding in which system components are connected directly to ground by individual leads should be avoided.

While simple in principle, series grounding is difficult to achieve. For example, components which are rack mounted are grounded in parallel. However, this seldom causes problems if they are connected to the a.c. power with the "high" and "low" sides comparable for each component and the racks themselves are grounded in series. The third wire safety ground provided with most instruments is a common source of ground loops. It is usually best to defeat these grounds and ground through the rack. A practical method is to supply power to all instruments in a rack through a three-wire multiple outlet box in which the ground wire has been disconnected from each outlet. Plugging them in "three-wire" keeps the "high" and "low" sides of the a.c. properly oriented for each instrument. Two

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safety precautions must be observed, however: (1) Be sure that grounding through the rack is electrically equivalent to each instrument's safety ground; if not make it so. (2) Ensure that the rack itself does not become accidentally ungrounded. Soldered connections help avoid this hazard.

In any complex system, the opportunity for unrecognized ground loops is large. For example, shielded cables are not an ideal way to ground major components such as instrument racks and EEG machines. If they are disconnected for any reason, the whole component becomes ungrounded which can be dangerous. A permanent independent ground is better. Then the shielded cable should have the shielding grounded at one end only; otherwise you have dual grounds and a possible ground loop.

Assuming the interference has been determined to be 60 Hz intrinsic to the system, one must find the ground loop. Monitoring one or more amplifiers at the output of the final stage, short the amplifier inputs together and isolate the amplification-monitoring equipment completely from the rest of the system except for the normal amplifier ground. This should eliminate the interference. Then reconnect power and grounds for each system component until the interference source is revealed by reappearance of the 60 Hz. Correct the problem by improved grounding, ungrounding, a.c. plug reversal, etc., and continue step by step until the entire system is interconnected. Obviously, if assembling a new or modified system for the first time, using this procedure initially may prevent much subsequent grief. Finally, suppose that isolating shorted-input amplifiers and monitoring equipment does not eliminate the 60 Hz. We have had this happen on two occasions which illustrate the bizarre and nefarious ways ground loops can occur. We ground our recording chambers to a specially installed ground separated from all other electrical grounds in the hospital. We then ground our amplifiers to the chamber and the remaining components are grounded in series as discussed above. On two occasions our amplifier outputs showed 60 Hz interference though isolated completely from the rest of the system. Disconnecting our main ground paradoxically eliminated 60 Hz. This could only mean that our recording chamber was grounded by some means unknown to us. Checking with an ohmmeter verified a relatively high resistance path to ground. A recheck verified that our chamber was not grounded by any obvious means, including a common error of grounding through the metal conduit of the chamber lighting and ventilating system. After a considerable period of consternation, the accidental ground was discovered to be a metal channel carrying cables overhead which rested on the metal recording chamber on one end and had, for convenience, been attached on the other end to a screw holding the grill of an air conditioning cold air return which was grounded.

The second experience was even stranger. After many hours of mystification, the sneak ground path was found to be bolts holding the vibration isolation rails of the chamber to the floor. The bolts contacted metal lathing of the ceiling below which in turn probably contacted water pipes or electrical conduits. Removal of the bolts, which were unnecessary in the first place, solved the problem.

Appendix

1. Model EZM-1 Electrode Impedance Meter, Grass Instruments Co., Quincy, Mass.
2. Speed-clave No. 777, Wilmot Castle Co., Rochester, N.Y.
3. Time Sterile Indicator Tape, Professional Tape Co., Riverside, Ill.
4. EC2 Electrode Cream, Grass Instruments Co., Quincy, Mass. Bentonite paste is used in the same application by many investigators. A formula for its mixture is in Cooper *et al.* (1969), Appendix B.
5. Cambridge Instrument Co., Inc., Ossining, N.Y.
6. Peripheral Nerve Stimulator, Model ST-4, Neurodyne Instrumentation, Napa, Calif.
7. #355 Prufex Conductive Knee Crutch Straps, American Hospital Supply, Edison, N.J.
8. Model 114, Wavetek, San Diego, Calif.
9. Model 901B, Grason-Stadler Co., West Concord, Mass.
10. Model 829E Electronic Switch, Grason-Stadler Co., West Concord, Mass.
11. Rye Industries, Mamaroneck, N.Y.; Telex, Communications Division, Minneapolis, Minn.
12. Type 1556-B Impact-Noise Analyzer, General Radio Co., West Concord, Mass.
13. Type 412 Sound Level Meter, H. H. Scott, Maynard, Mass.
14. Universal Counter-Timer, Model CF 635, Anadex Instruments, Inc., Van Nuys, Calif.
15. Model 350D Attenuator Set, Hewlett-Packard Co., Palo Alto, Calif.
16. Model PS-2 Photo Stimulator, Grass Instruments Co., Quincy, Mass.
17. Industrial Acoustics Co., New York, N.Y.
18. Type 320 Event Counter, Digilin Digital Instruments, Division of Dura-Containers, Glendale, Calif.

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Chapter 4

The Analysis of Scalp-Re

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