2 Basic Instrumentation, Acquisition, and Recording Considerations

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Abstract
This chapter provides more information about the basic science behind stimulus generation and presentation, auditory evoked potential (AEP) instrumentation, and various stimulus- and subject-based factors to consider for the acquisition of AEPs. With an increased familiarity of how AEP equipment functions and basic knowledge regarding recording parameters, one can confidently set up protocols and record all the AEPs discussed within this text.

Keywords: instrumentation, digital signal processing, differential amplifier, filtering, signal averaging, electrodes

2.1 Introduction

The instrumentation involved in recording auditory evoked potentials (AEPs) may have evolved tremendously over the last 70 years due to the advent of signal averaging and digital signal processing (DSP), but the core concepts regarding the recording of AEPs generally have not. Today's instrumentation typically includes a desktop or laptop computer, an amplifier box, an electrode box, electrodes, and one or more transducers (e.g., insert earphones, supra-aural headphones, bone oscillators, and speakers). The transducers are used to present a variety of stimuli to one or both ears, whereas the electrodes act like antennas, picking up voltage changes from underneath the skin surface. The amplifier is necessary to bring the small-amplitude electroencephalogram (EEG), and subsequently the AEP, into the voltage range of the computer. The computer is initially involved in analog-to-digital conversion of the incoming EEG, but then it will also filter unwanted signal frequencies and perform signal averaging so that the AEP can be extracted. However, there can be no AEP unless the computer also presents stimuli with specific physical characteristics at necessary intensity levels, stimulation rates, and so on.

2.2 Signal versus Noise

When there is no direct sensory stimulation (e.g., acoustic stimuli to the ears), the neuronal activity of the cortex is quite dominant compared with noncortical neurons and can easily be recorded with electrodes placed on the scalp. This cortical activity is called the electroencephalogram (EEG). As with any signal that can be represented by simple or complex waves, the ongoing EEG is a biologic wave that is somewhat noiselike in appearance and can exhibit voltages as high as 50 to 100 µV. In a relaxed person, the EEG can be as low as 10 to 20 µV. A spectral analysis of the EEG in a person who is awake would show frequencies ~20 Hz and higher. However, when a person becomes drowsy and then falls asleep, the EEG drops to ~10 and 3 Hz, respectively. Conversely, when a sensory system (e.g., the auditory system) is stimulated, there is a propagation of neuronal activity through the peripheral and central nervous systems (PNS and CNS). Sensory stimulation produces what is called an evoked potential (EP) or evoked response (ER). In contrast to the EEG, EP signals are much smaller in amplitude (i.e., usually no more than a few microvolts). Indeed, any EP would be virtually lost against the larger EEG without sophisticated techniques to extract the EP (desired signal) from the EEG (noise, or unwanted signal). The signal of interest is recorded using a digital computer for later processing, analysis, and interpretation. Basic tenets of DSP are described in the next section.

2.3 Digital Signal Processing

To understand how digital computers aid in the recording of AEPs, it is helpful to understand the dichotomy between continuous (analog) and discrete (digital) signals. Continuous signals are those that can be represented by a value at all points in time, no matter how small or how many decimal points there are.[1] Both EEGs and AEPs coming from the head surface and all stimuli presented acoustically, by nature, are continuous signals. Discrete signals have a limited number of decimal places;[1] as a result, some information about an otherwise continuous signal may be lost once converted to a discrete signal. Discrete signals can undergo DSP. Stimuli presented from a computer through earphones and all visual displays of the AEP and/or EEG on a computer monitor screen will be in the form of a discrete signal; thus, conversion from analog to digital (A-D) and from digital to analog (D-A) can be appreciated during routine AEP testing.

A-D conversion is a two-step process involving sampling and quantization.[1,2,3] Sampling involves breaking a continuous signal down into a limited number of manageable units, called samples, each having equal time duration. As an example, the auditory brainstem response (ABR) is commonly recorded using a time window of 10 milliseconds and a fixed number of sampling points (usually 256). This means that the ABR will be divided into 256 pieces, with each piece (sample) having a duration of 0.0390625 milliseconds. Quantization involves breaking down a continuous signal into manageable amplitude units, called steps. From the point of view of electronic or biologic signals, amplitude values are really voltage values. Computers process information in binary digits (or bits) with strings of 0 s and 1 s, and a 16-bit computer has the ability to quantize amplitude values into 65,536 discrete amplitude steps.

Perhaps the most important aspect of DSP for AEP testing is sampling rate (also called sampling frequency). Sampling rate is important because it determines the maximum signal frequency that can be digitized.[3] The Nyquist theorem states that the sampling rate should be at least two times the highest frequency in the signal of interest.[2,3,4,5] The highest frequency of interest in the signal is called the Nyquist frequency. If this requirement is not satisfied, a situation called aliasing occurs in the A-D process, and the digital waveform will misrepresent the

analog signal[1,3] A distortion is created by the folding of frequency components higher than the frequency of interest onto lower-frequency components.[3] For example, a 75-Hz sine wave sampled at a rate of 100 samples per second will erroneously be digitized as a 25-Hz sine wave. However, to achieve a reasonably faithful representation of a continuous signal, sampling rates higher than a factor of 2 may be necessary.[3,4,6] This discussion surfaces again later in this chapter with respect to filtering and signal averaging.

2.4 Time and Frequency Domain

Auditory stimuli and AEPs both occur in time as waveforms, and both can be analyzed in the time and frequency domains. It may be helpful to understand that both auditory stimuli and AEPs are often referred to as signals to differentiate them from noise. A time-domain analysis evaluates the amplitude of a signal over time, and the signal appears as a waveform with alternating positive and negative values. In contrast, a frequency domain analysis (e.g., a spectrum) removes the element of time to reveal the spectral energies of the signal as the waveform is translated to its respective amplitude values across frequencies. An AEP is nothing more than a complex waveform (i.e., a combination of many frequencies or sine wave components). Thinking about an AEP in terms of its spectral energy is a concept that is not always intuitive for clinicians who are used to visualizing an AEP represented as a waveform in the time domain. However, it is important to understand this concept, which will become particularly evident in later sections discussing filter settings. ▶ Fig. 2.1 illustrates an example of an AEP in its respective time and frequency domains.

2.5 Instrumentation

2.5.1 Stimulus Generator

Most AEP systems are capable of generating a variety of stimuli, and the clinician may have some control and flexibility in defining certain physical parameters of a stimulus. Clinically, the most commonly used stimuli include 100-microsecond clicks and short-duration tone bursts. More recently, chirps (broadband and frequency-specific) have also become available. With auditory steady-state responses (ASSRs), signals are typically amplitude- or frequency-modulated tones, or they may use a combination of both, referred to as mixed modulation. Other AEPs may be evoked by simple speech stimuli (e.g., /da/). Typically, the equipment allows the clinician to import stimulus files (e.g., .wav files) that are not default selections within the software, as is often the case if a speech stimulus is desired. The type of stimulus used and its characteristics have important effects on AEPs; these stimulus effects vary depending on the signal of interest and therefore are discussed throughout the text for each individual AEP.

2.5.2 Transducers

Although the choice of transducer is up to the clinician, tubal-style insert earphones (e.g., ER-3A; Etymotic Research Inc., Elk Grove Park, IL) are more commonly used for AEPs compared with supra-aural headphones (e.g., TDH-49; Telephonics Corporation, Huntington, NY). However, both are commonly reported in the literature and used by clinics around the world. As with audiometry, the same advantages for the use of insert earphones with AEPs generally apply (e.g., sanitary and comfortable), but the most important advantage is the physical and temporal separation of the transducer box from the ear and electrodes. The tube produces a small time delay of ~0.8 milliseconds and permits a separation of any stimulus-related artifact from contaminating the AEP as it is being recorded. In most cases, the stimulus artifact will not affect the recordings when insert earphones are used; however, a ringing stimulus artifact from a TDH-49 supra-aural headphone may obscure or even enhance wave I artificially. For ABR, in particular, care must be taken to physically separate the insert earphone transducer box from the electrode wires as much as possible. In some cases, it is possible for the stimulus artifact to be so large as to cause the artifact rejection to overreact, thereby affecting the averaging process.

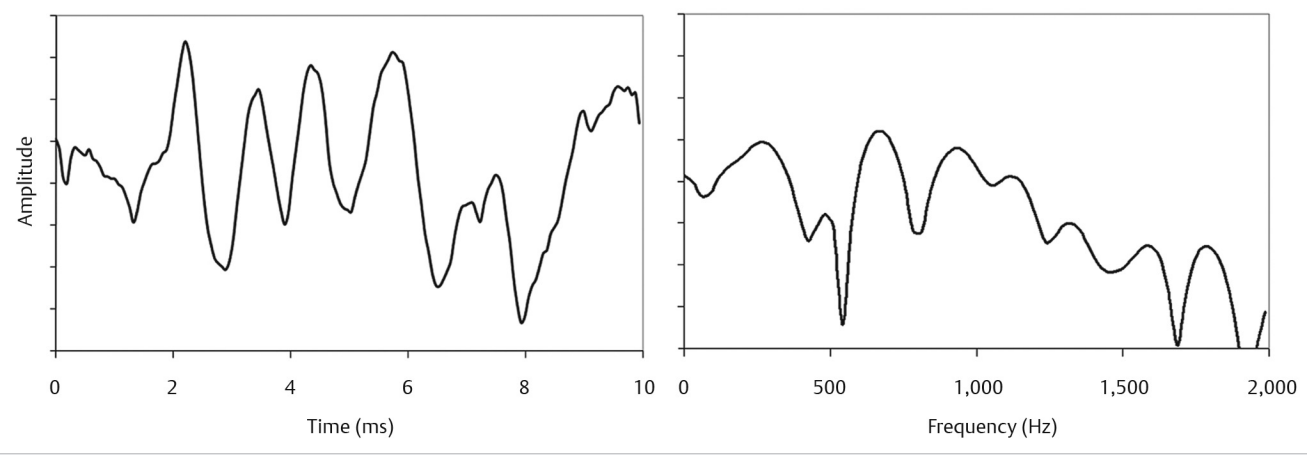

Fig. 2.1 The auditory brainstem response (ABR) in the time (*left*) and frequency (*right*) domains. The time domain shows the ABR as having a series of several waves within a 10-millisecond time window. The frequency domain shows the spectral energies within the ABR with the element of time removed. Notice that spectral energy is greatest between ~200 and 1,000 Hz, with major spectral peaks around 250, 600, and 900 Hz.

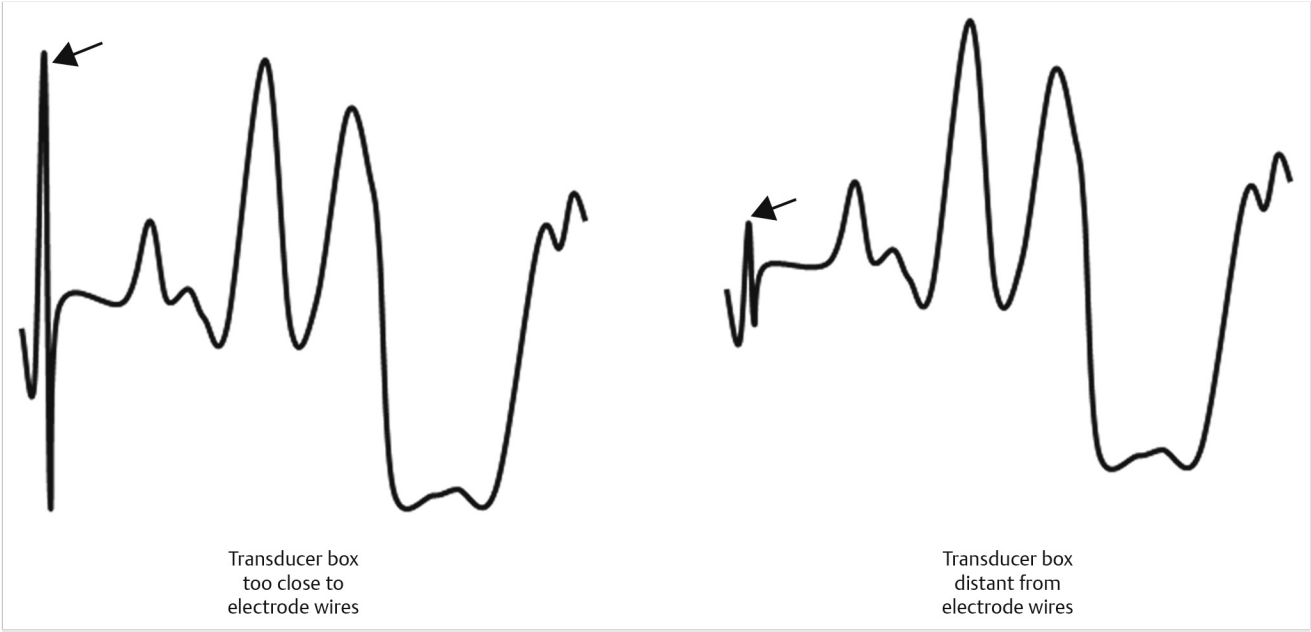

Fig. 2.2 The physical relationship of the insert earphone transducer box and the electrodes on the magnitude of the stimulus artifact (*arrows*) seen in an auditory brainstem response (ABR) recording.

▶ Fig. 2.2 shows an example of stimulus artifact when the insert earphone transducer is close to the electrode wires and when it is placed at a distance.

2.5.3 Trigger

The trigger is key to the recording of all AEPs and works in tandem with signal averaging. In general, the trigger is a digital pulse or word that lets the averaging computer know precisely when each stimulus is being presented. Once the recording time window is defined, the trigger and stimulus onset are essentially synonymous with time zero in the analysis time window. While all commercially available EP systems have their own self-contained triggers as each stimulus is presented, some EP systems may accept a trigger from another computer system (or stimulus generator) that is not associated with the recording system. In this way, novel stimuli and/or stimulus paradigms often seen in research may be used to evoke the AEP without having to acquire research-grade equipment.

2.6 Acquisition Parameters

The primary technical problem of recording brain electrical activity from the scalp is that the ongoing EEG contains both the AEP of interest (i.e., signal) and various sources of noise, both physiologic and nonphysiologic. Sources of physiologic noise include spontaneous brain activity, electromyogenic potentials, corneoretinal potentials, and electrodermal potentials. Some nonphysiologic noise sources are electromagnetically induced potentials (e.g., 60 Hz line noise), internal electrical instrument noise, and electrode polarization. With few exceptions, AEPs are smaller in amplitude than the background EEG, and thus they have a poor signal-to-noise ratio (SNR). To extract the smaller AEP signal and attenuate noise (i.e., improve SNR), several techniques are necessary to condition the AEP signal for later analysis: amplification, filtering, and averaging. The use of metal electrodes placed on the scalp permits the collection of brain electrical voltages into the recording equipment. Specific details regarding acquisition parameters of individual AEPs are located throughout this text; general information regarding SNR techniques and application of electrodes is addressed in this section.

Table 2.1 Interchangeably used terminology for electrode sites

Noninverting	Inverting	Ground
Active	Reference	Common/ground
Positive (+)	Negative (–)	Common/ground
Input 1	Input 2	Common/ground

2.6.1 Differential Amplification

Amplification of AEPs serves two purposes: to reduce background noise through differential recording and to bring the signal of interest into the range of the A-D converter.[7,8,9] For a basic differential recording, a minimum of three electrodes is required: noninverting, inverting, and ground electrodes.[4] Electrode terminology can be confusing, as multiple terms are used interchangeably to describe the different electrode sites (see ▶ Table 2.1 for a summary). During amplification, any signal (and noise) that is common at the scalp to the positive and negative inputs will be reduced, while signals that differ between these inputs are amplified.[6,7,9,10] The process of canceling signals common to both inputs is referred to as common-mode rejection (CMR; ▶ Fig. 2.3).

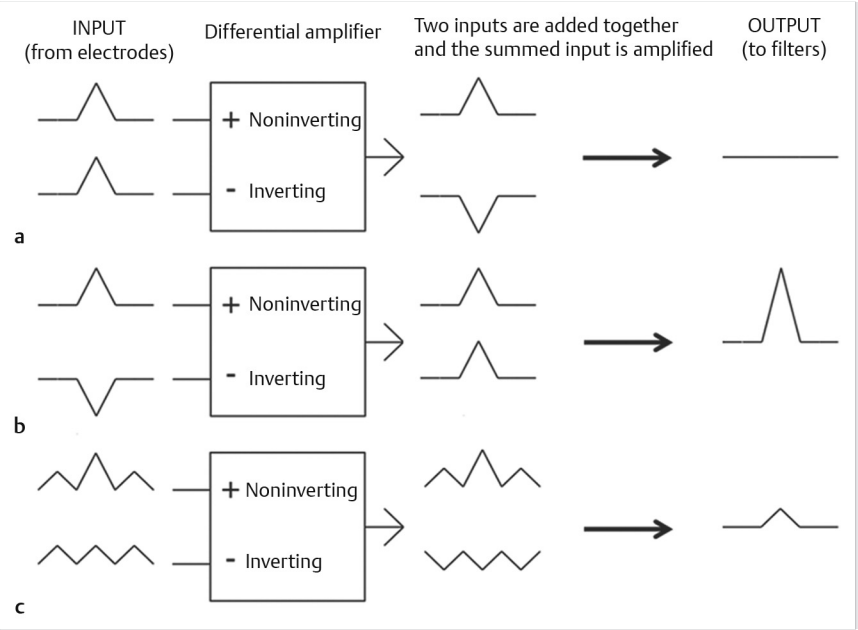

Fig. 2.3 Function of the differential amplifier and common-mode rejection. Tracings on the left-hand side of the figure are inputs from the electrodes. Positive (+) input is noninverting, and negative (–) input is inverting. Tracings on the right-hand side of the figure are outputs of the differential amplifier to the filters. **(a)** Signals common to both inputs (+ and –) cancel at the output. **(b)** Signals uncommon to both inputs amplify at the output. **(c)** Signals common to both inputs (low-amplitude peaks) were canceled at output, whereas the slightly larger peak at the noninverting input is preserved and amplified.

How the CMR process works within the operation of the differential amplifier is frequently confused. Specifically, why is the negative input of the differential amplifier called the inverting input? Additionally, how are the signals combined within the differential amplifier? The first question can be answered by understanding the physical design of the differential amplifier. Within the differential amplifier are two single-ended amplifiers that are mirror images of one another, each sharing a common ground.[10] One of the amplifiers forces the incoming signal at the input to become inverted. Thus, any electrode connected to this input will be referred to as the inverting electrode. The second question can be answered in the way the CMR process works within the differential amplifier. Although the goal is to obtain the difference between the two inputs, the differential amplifier does not perform any subtraction; it can only add signals. With the "mirror image" setup of the single-ended amplifiers, the differential amplifier will add the inverted input to the noninverted input, thereby "amplifying the difference" between the voltages present simultaneously at the two inputs.[10] Thus, the voltage output of the amplifier will be zero whenever the voltages at the two inputs upon entering the differential amplifier are identical (hence common mode).

Although differential amplification greatly improves SNR, it is not sufficient alone for the enhancement of AEPs and attenuation of noise. There are at least two primary reasons for this dilemma. First, noise has only a moderate correlation between the two amplifier inputs, which implies that noise will not cancel out entirely.[4] Second, the recording of AEPs reflects a potential (i.e., voltage) difference between two sites, not over a single site. For this reason, CMR works best when the inputs record activity at electrodes placed at sites of opposite bioelectric polarity[4] or in the appropriate plane relative to the signal's neuroanatomical dipole (see Chapter 4 regarding dipoles). ▶ Fig. 2.4 illustrates the effect of proper electrode placement with respect to the differential amplifier and neuroanatomical dipoles of the ABR.

In addition to differential amplification, there is additional amplification, referred to as gain, that can be applied to the recorded response. The AEP software will include gain as a parameter that can be modified within the acquisition parameters. Remember that AEPs are quite small (e.g., no more than a few microvolts); therefore, gain settings are set to magnify the response to values to 50,000, 75,000, or 100,000 times. Amplification settings depend not only on the AEP of interest but also on other protocol parameters (e.g., electrode placement). For example, gain does not need to be nearly as high for tympanic membrane electrode placement (e.g., gain = 50,000) as it does for ear canal electrode placement (e.g., gain = 75,000) with electrocochleography (ECochG; see Chapter 12).

2.6.2 Filtering

Filtering is the next technique that is used for improving SNR. As with complex sound waves, all biological signals can be broken down into component frequencies, with each frequency having its own amplitude.[8] Because the signal of interest may occur together with unwanted noise,[4,5,11] filtering provides a means of suppressing noise that is not in the frequency band associated with the AEP. Filters, by definition, attempt to pass signals of interest while rejecting noise. Noise can be defined as any part of a signal detected by the electrodes that is not of interest.[6,9] What is preserved and what is suppressed during AEP recording depends on the filter settings. The spectral (frequency) composition of the AEP of interest will help determine appropriate filter settings. The spectral composition of an AEP, and thus its greatest spectral energy, can be determined by performing a fast Fourier transform (FFT) to break down the AEP into component frequencies. ▶ Fig. 2.5 illustrates an FFT on a cortical event-related potential (CERP) waveform with energy between 1 and 50 Hz.

Analog versus Digital Filters

Both analog and digital filters are frequently used in AEP recordings, each with major differences. Analog filters are

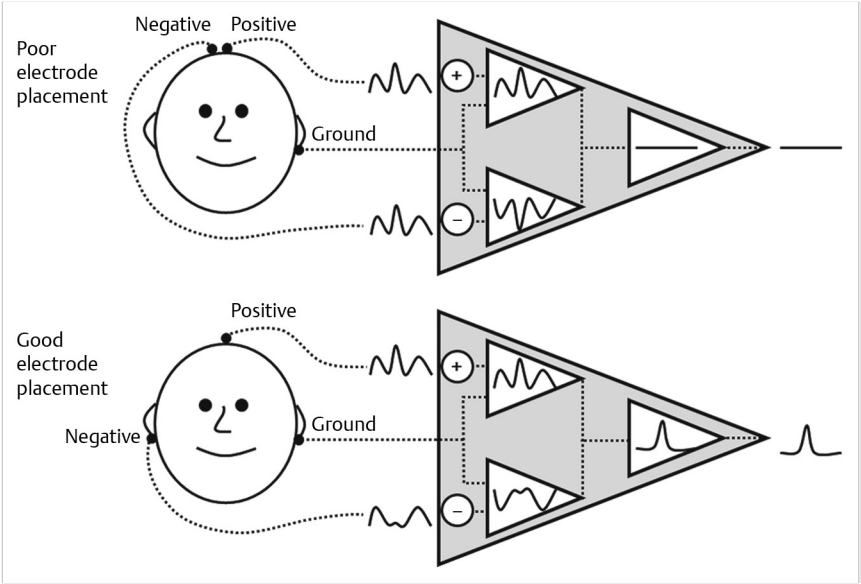

Fig. 2.4 Effect of electrode placement on common-mode rejection/differential amplification for the auditory brainstem response (ABR). In the top half of the figure, electrodes are placed close together on the scalp, resulting in similar activity being received by both. By inverting the input from the negative electrode and adding it to the input from the positive electrode, essentially everything is canceled out, and the output of the amplifier is zero. In the lower half of the figure, the positive electrode is at vertex, whereas the negative electrode is on the ipsilateral ear. This electrode placement will ensure that different activity relative to the evoked response is recorded, as the electrodes are on opposite ends of the signal pathway; however, the noise should be similar. When the inputs are added together, the noise (common activity between the electrodes) is canceled, whereas the signal is amplified.

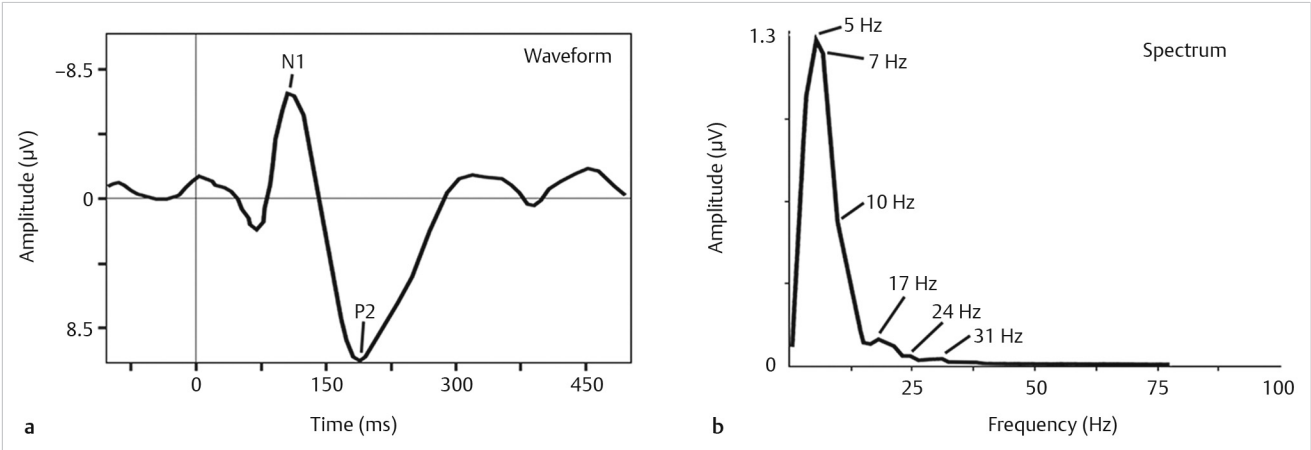

Fig. 2.5 Illustration of fast Fourier transform (FFT) on a cortical event-related potential (CERP) waveform. **(a)** Averaged waveform represented in the time domain (millisecond). **(b)** Applying FFT on the waveform, the spectral energy is represented in the frequency domain (Hz) with energy up to ~50 Hz. The greatest spectral energy occurs ~5 Hz. Thus, the bandpass filter during acquisition should have cutoffs as low as 0.01 Hz and as high as 100 Hz (i.e., twice the Nyquist frequency).

physical devices that take any real numerical value (plus and minus infinity) of an electrical signal that varies continuously in voltage and time.[4] Analog filters are used in differential amplifiers because the brain's electrical signal is continuous. Digital filters, by contrast, are numerical algorithms performed by a computer. Digital filtering is particularly useful after A-D conversion has taken place and discrete numerical values are stored in memory. A-D conversion has more relevance in the statistical averaging process, which is discussed in the section on signal averaging.

Filter Designs

Filters are characterized by the range of frequencies that they allow to pass and those they reject or stop. There are four basic filter designs specified by cutoff frequencies: high-pass, low-pass, bandpass, and notch (band-reject) filters. High-pass filters attenuate low-frequency signals, such as direct current (DC) signals, whereas low-pass filters attenuate high-frequency signals, such as myogenic artifact and radio transmissions.[10] Using both high- and low-pass filters together in the appropriate way can create either a bandpass or a notch filter.

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In general, filter settings for various AEPs have already been well established. Filter cutoffs are based upon known spectral energies of the AEP and are broad enough so as not to cause unnecessary waveform distortion and aliasing, particularly if the low-pass filter is too low. To safely avoid aliasing, it is recommended that the low-pass filter cutoff be set at least four times the Nyquist frequency, but may well be much higher due to the number of sampling points available.

Pitfall

AEP recordings are susceptible to 60-Hz electrical line noise. Activating the 60-Hz noise notch may be fine to use for some AEPs, but not all. The 60-Hz line noise can emanate from sources other than the power outlet and may arise from other electronic equipment in a room. It is recommended that clinicians first identify the source and determine if the 60-Hz artifact can be minimized or reduced either by turning unnecessary equipment off or by moving them away from the AEP system. In some instances, simply moving the AEP system to a different location in the same room or to another room altogether does the trick.

2.6.3 Signal Averaging

After differential amplification and filtering, the third way of improving SNR is signal averaging AEP signals time-locked to presented stimuli. The basis for the SNR improvement by signal averaging is due to noise (i.e., EEG) not being time-locked to the external stimulus.[4,5,7] The EEG is assumed to be random and statistically stationary (e.g., values normally distributed around the mean) at all time intervals through the averaging process. Thus, noise will cancel itself out, whereas time-locked signals sum together. ▶ Fig. 2.6 shows a simplified example of how signal averaging works to minimize noise.

When the incoming signal is sampled from the surface of the head, only a set amount of the signal is sampled for a fixed duration of time. Generally, the entire EEG is not recorded. Instead, the EEG is chunked into limited time windows or epochs during which the AEP is expected to appear following stimulus presentation. The duration of the epoch should be at least as long as the period of the lowest frequency of interest for the AEP waveform of interest to be seen clearly. The beginning of each epoch should coincide with the presentation of the stimulus in a predetermined manner so that the unaveraged responses (i.e., signal embedded in EEG) elicited by the stimulus are time-locked to one another in the averaging process.[10] Recall that the EEG contains the AEP of interest, but it is buried within the noise, and the entire epoch has been digitized. During signal averaging, the digitized epochs are mathematically averaged into the singular response waveform seen on the computer monitor screen.

The rate of improvement of SNR is proportional to the square root of the number of epochs, or the square root of the number of stimulus presentations (on).[4,5] The amount of SNR depends on the type of signal being averaged and the amount of concurrent noise.[5] For example, the ABR may require several thousand stimulus presentations because of signal amplitudes < 0.5 µV, which are on the order of 50 to 100 times smaller than the amplitude of noise (~50 µV). Long-latency potentials (e.g., N1/P2), on the other hand, require only hundreds of sweeps or fewer as their amplitudes are larger (~5 µV). ▶ Fig. 2.7 illustrates an example of SNR improvement for the ABR with 50, 500, and 1,500 stimulus presentations.

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Terms such as *stimulus presentations*, *stimulus repetitions*, and *sweeps* are generally synonymous. They each imply the number of epochs accounted for in the average AEP. The clinician will usually set the number of times the stimulus should be presented or repeated prior to the start of the recording. Many AEP systems today may present more than the predetermined number of stimuli if some of the epochs were rejected (see section "Artifact Rejection").

2.7 Electrodes

Electrodes form the primary connection between the patient and the AEP recording equipment. Mere application of an electrode to the skin or scalp is not suitable for recording bioelectrical activity because the outermost skin layer (i.e., the stratum corneum) acts as an electrical insulator.[7,12] To improve the electrical conductivity, the skin is abraded to remove dead skin cells, and an electrolyte gel or paste (usually a sodium chloride solution) is applied. However, this interface between the electrode and the skin will continue to have some degree of electrical opposition known as electrode impedance.[7,8,12]

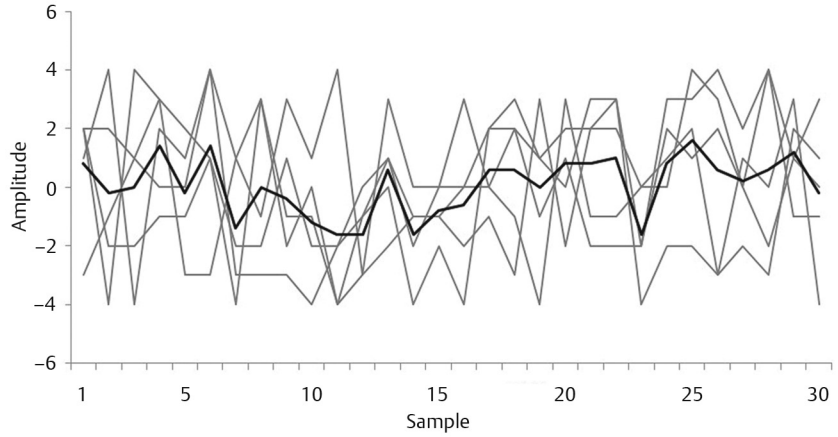

Fig. 2.6 A simplified example of how noise is minimized with signal averaging. Five separate noise waveforms made up of 30 samples each are shown as *gray lines*. Notice that they appear quite different from each other, with random values in whole integers varying between –4 and 4. The *black line* is the mathematical average of the five *gray lines*. Although still somewhat random and zagged, the *black line* is smoother in appearance, with values in a narrower range between –2 and 2. This reduction in overall amplitude accomplished by averaging is in effect how the random noise signals are gradually canceled out.

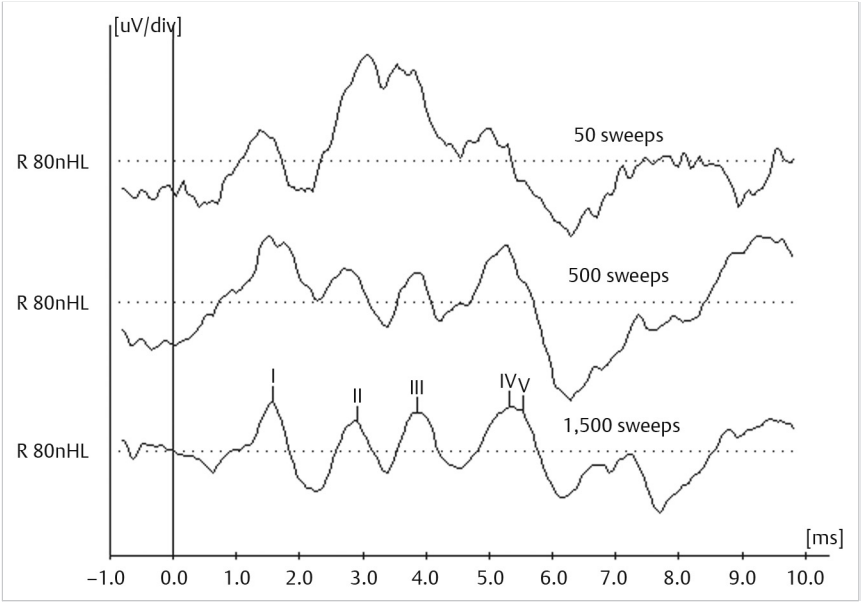

Fig. 2.7 Examples of signal-to-noise ratio (SNR) improvement in the auditory brainstem response with 50 (*top*), 500 (*middle*), and 1,500 (*bottom*) sweeps. Although the middle and bottom recordings are similar, these were obtained from a very relaxed patient.

2.7.1 Electrode Impedance

The electrode impedance is determined by several factors, including the surface area of the electrode, the tissue to which it is attached, any debris in between (e.g., oil, dirt, and sweat), the electrolyte solution, and the type of metal used for the electrode. The type of metal used is of particular importance in terms of voltages and impedances that are developed when used in conjunction with electrolytes.[10] Good conducting metals are silver, gold, platinum, lead, tin, and stainless steel; because they have low impedances and low electrode potentials.[7,10] Some electrodes can be designed that allow free exchange of ions across an electrical double layer. An example is the silver–silver chloride (Ag-AgCl) electrode formed by silver plated with salt, which lowers impedances further.

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As a general rule, Ag-AgCl electrodes will work with most AEPs, from ABR to CERP, and will remain stable regardless of recording time.[13]

For optimal recording, electrical impedances should not exceed 5 kΩ.[7,10] Because a minimum of three electrodes are required for differential recording,[4] it is imperative that the electrode impedances be balanced between all electrodes employed. The reason that the impedances must be balanced is because bias can be implicated in the frequency sensitivity and the optimization of the CMR of noise.[7,10] As a rule, it has been suggested that interelectrode impedances do not exceed 2 kΩ.[7]

2.7.2 Electrode Types

In general, electrodes are long metal wires with insulative coating. At one end of the electrode is a connecting plug to the recording equipment, and the other end connects to the patient. The end that is connected to the patient comes in several different shapes, sizes, and styles, and will vary depending on the clinical application or the type of AEP desired. Except for needle electrodes that may be used for intraoperative monitoring purposes, most scalp electrodes are either disk- or cup-shaped, or they are pre-gelled disposable types. ▶ Fig. 2.8 features several electrode types commonly used by audiologists.

2.7.3 Electrode Placement

To facilitate laboratory comparison of AEP data, Jasper[14] developed the international 10–20 system of electrode placement (or 10–20 system). The 10–20 system has been the standard for electrode placement for many years, and it provides guidelines for the placement of 21 electrodes. The electrodes are placed manually following measurement from standard positions on the scalp, that is, nasion, inion, and preauricular points. The strength of this system is that by making such proportional measurements, variations in head size and shape are accommodated. Each electrode is given a designation based on brain area as well as a subscript letter or number to indicate midline or homologous areas of the left and right hemispheres. Brain areas are designated frontal (F), parietal (P), occipital (O), temporal (T), and central (C). Even numbers are associated with the right hemisphere and odd numbers, with the left. Midline electrode locations are labeled with a "z" (zero). Also included in the 10–20 system are electrodes Fpz (frontal pole), A1 and A2 (earlobes), Cb1 and Cb2 (cerebellar), and Pg1 and Pg2 (pharyngeal). Other designations later used in audiology include M1 and M2 (mastoids), Ai (ipsilateral earlobe), Ac (contralateral earlobe), and C7 (nape of the neck).[13] ▶ Fig. 2.9 shows the organization of commonly used electrode sites in audiology.

A review of the vast scalp-recorded EP literature will convey a wide variety of reference electrode sites employed. A reference is required in recording AEPs because voltages can be measured only as a difference between two scalp points. With respect to scalp AEP recordings, Wolpaw and Wood[15] suggest that the optimal site is a place on the head or body where the potential field is most stable. Whenever possible, the reference

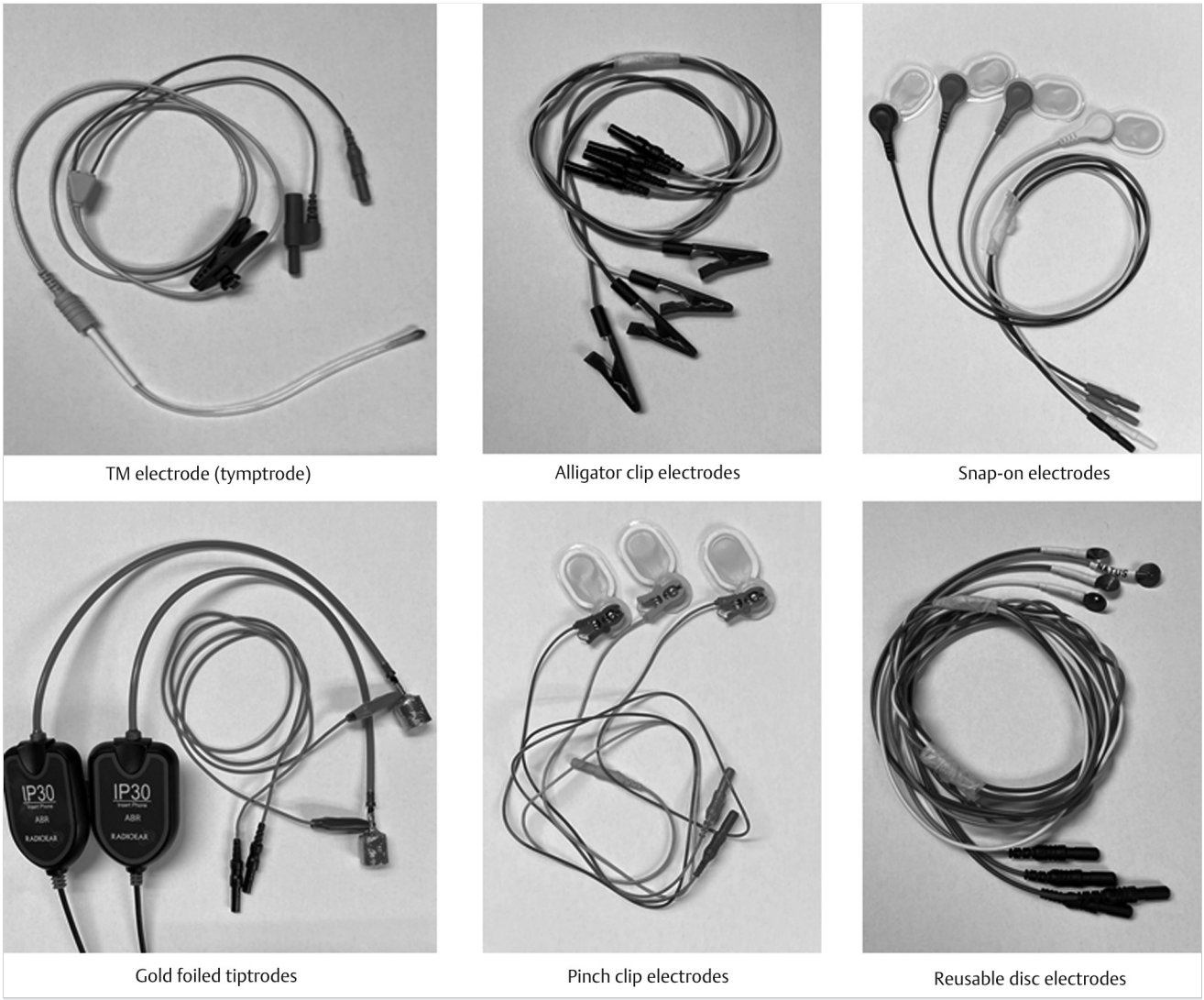

Fig. 2.8 Some examples of electrodes and connectors used by audiologists. Note Alligator clips are often connected to tab electrodes (not shown). Also, the adult size gold foil TIPtrode inserts are shown, but they also come in a smaller/pediatric size.

electrode should not be close to the generator site of interest and should not favor one generator over another, particularly in hemispheric studies.[16,17] Wolpaw and Wood[15] have shown that nasion, earlobes, and mastoids work well as reference sites. McPherson and Starr[18] also advocate the use of a noncephalic site on the nape of the neck (C7). ▶ Table 2.2 shows the most common electrode montages employed for different AEPs.

2.7.4 Number of Electrodes versus Number of Channels

Beginning clinicians often confuse the number of recording channels with the number of electrodes that are needed. Generally, a minimum of three electrodes are required to complete the circuit for one channel.[4] Two electrodes go into each of the positive and negative inputs of the differential amplifier, and the remaining electrode goes to ground. Many AEPs can be recorded with a single-channel setup using either Cz or Fz (noninverting), Ai (inverting), and Ac (ground). The most common example of a two-channel setup is the simultaneous ipsilateral and contralateral ABR recording where each ear serves as the inverting input for separate differential amplifiers, Cz is physically linked by a jumper cable plugged into both noninverting inputs, and ground is Fpz. Thus, four electrodes and a jumper are required, but only two channels are involved. Here a single noninverting electrode site is used (Cz); however, clinicians are using the independent references that may be used in interpretation.

A different two-channel setup is often used with middle latency responses (MLRs) and is recorded simultaneously from both temporal lobe regions. In it, C3 (left temporal lobe) and C4 (right temporal lobe) serve as noninverting inputs to separate differential amplifiers, the ears (A1/A2 or M1/M2) serve as reference electrodes, and ground is on Fpz. In this example, five electrodes were required for only two channels. In preplanning, it often helps to draw your desired electrode montage on paper and stick with commonly used protocols, particularly with

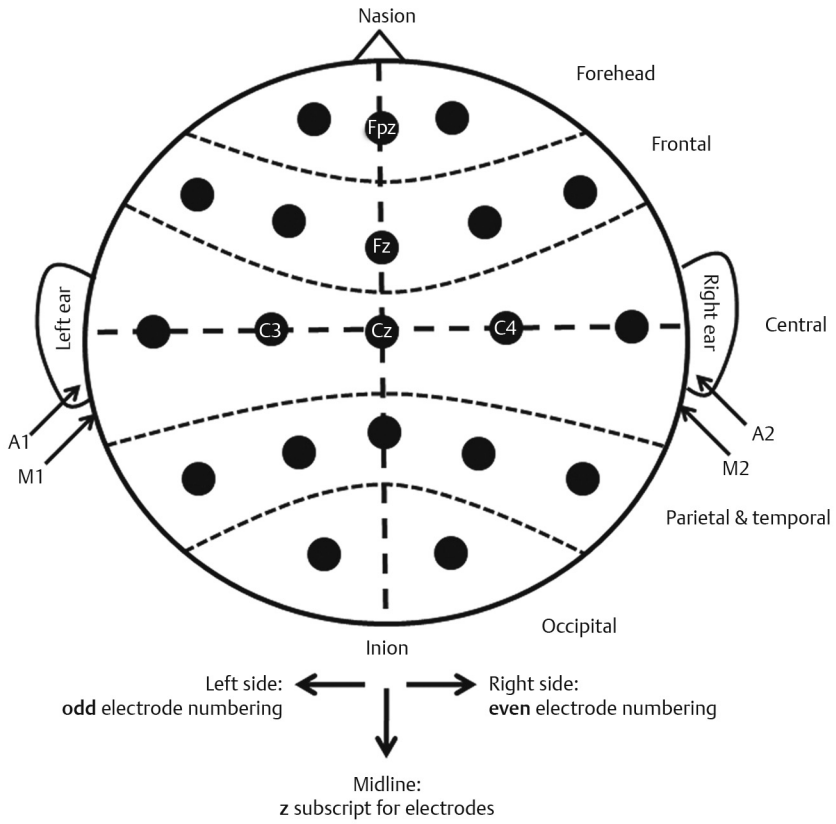

Fig. 2.9 Illustration of 10–20 system of electrode placement. Electrodes are placed on the scalp in designated areas based on measurements between nasion, inion, and preauricular points. See the text for a description of the electrode nomenclature based on the 10–20 electrode placement system.

Table 2.2 Commonly Used Electrode Montage for Major AEPs

AEP	Noninverting	Inverting	Common/ground
ECochG	Ac	Ipsilateral TM or ear canal	Fz
ABR	Cz or Fz (avoid Cz for infant testing)	Mi or Ai	Mc or Ac
MLR	Cz or Fz for single channel, C3 and C4 to investigate electrode effects	Ai (avoid mastoid due to PAM artifact)	Ac
CERP	Cz (Pz for P300)	Mi or Ai (some use linked mastoids)	Fz

Abbreviations: ABR, auditory brainstem response; AEP, auditory evoked potential; CERP, cortical event-related potential; ECochG, electrocochleography; MLR, middle latency response; PAM, postauricular muscle; TM, tympanic membrane.

placement of the noninverting and inverting electrodes. Here independent recordings on each side of the head is possible to evaluate hemispheric symmetry (or lack thereof). Various montage examples are illustrated in ▶ Fig. 2.10.

2.8 Recording Considerations for Auditory Evoked Potentials

2.8.1 Electrode Array and Number of Channels

The way in which the different electrodes are arranged on the individual being tested is dependent on the anatomy and physiology behind the AEP of interest. This arrangement is commonly referred to as the electrode array. Remember, for differential amplification to be maximally beneficial, it is important to plan out your electrode array (montage) based on the neuroanatomical organization of the underlying dipoles. The number of channels necessary for recording depends on the AEP of interest and the reason for testing. Most AEPs can provide sufficient information with a single recording channel. A single recording channel is the simplest electrode setup, with one noninverting (active) electrode, one inverting electrode (reference), and one ground electrode. There are, however, certain test protocols that require extra channels (i.e., additional active electrode sites) to obtain all the necessary information for appropriate test interpretation. For example, multiple channels are often used to record an MLR for neurodiagnostic purposes to check for the presence of electrode effects (see Chapter 9). Additional channels are also recommended to monitor eye-blink artifact during CERP recordings (see Chapter 10).

2.8.2 Time Window

The time window is defined by the amount of time both before and after the presentation of the stimulus that will be analyzed

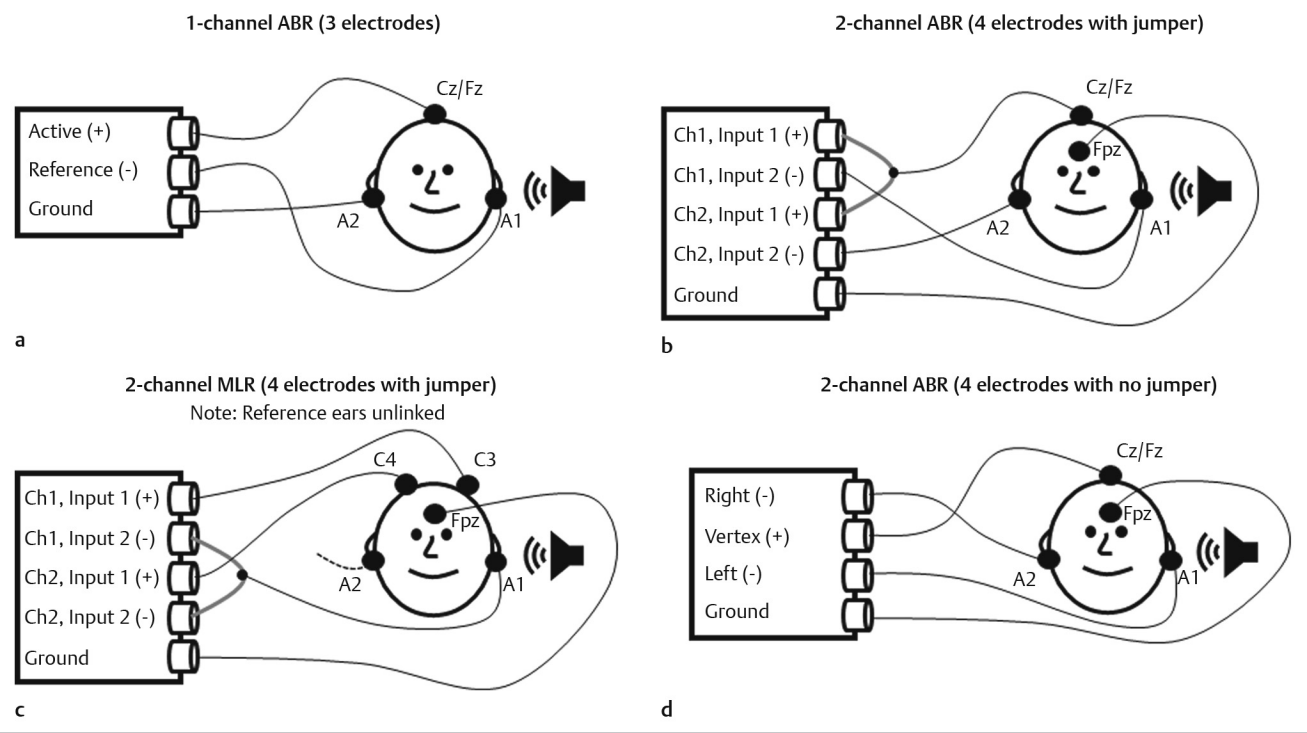

Fig. 2.10 Illustration of different electrode montages and connections. **(a)** One-channel auditory brainstem response (ABR) using three electrodes and three connections. **(b)** Two-channel ABR using four electrodes and five connections (input 1 of both channels is jumpered). **(c)** Two-channel middle latency response (MLR) using five electrodes and five connections (input 2 of both channels is jumpered). **(d)** Compare to **(b)**, two-channel ABR using four electrodes and four connections (no jumper needed for this setup). See the text for more information.

in the recording. Therefore, the time window will be chosen based on the expected latencies of the AEP of interest. It is important to choose a time window that is sufficiently long enough to capture the entire AEP while not including much response information beyond the components of interest. For example, waves I to V of the ABR are typically recorded within the first 6 milliseconds after the stimulus. A time window of 10 milliseconds is often chosen for neurodiagnostic ABR testing. However, there are stimulus and subject factors that can increase the latency of the response (e.g., low-frequency stimuli, decreased stimulus intensity, infants with immature central auditory nervous systems). In these cases, the time window will be increased, but only enough to account for the small change in latency (e.g., time windows of 15–25 milliseconds). It is important to choose an appropriate time window. Too short a time window may cut off relevant waves. Too long a time window will decrease the sampling rate and thereby decrease your time resolution (i.e., increase sample duration).

2.8.3 Sampling Rate

Sampling rate has an intimate relationship with the time window, especially when a fixed number of sampling points are chosen: 256, 512, and sometimes 1,024. Most commercially available AEP systems give at least two of these choices. Sampling rate can then be determined by dividing the time window (in seconds) into the number of points. For example, the ABR is often recorded using a time window of 10 milliseconds (or 0.01 seconds). If we chose 256 sample points, 256/0.01 = 25,600 samples per second (or Hz). If the Nyquist frequency in the ABR is around 1,000 Hz, it must be sampled at least 2,000 Hz, which means that a sampling rate of 25,600 Hz is more than plenty to sample the ABR with high temporal resolution. In fact, at this sampling rate, each sample duration is ~0.039 milliseconds. Realize, however, as the time window increases, the sampling rate will decrease, and it will be important to ensure that the Nyquist theorem is never violated by knowing beforehand the spectrum of the AEP of interest (recall from ▶ Fig. 2.1). Some authors suggest that the sampling rate be no less than four times the Nyquist frequency. ▶ Fig. 2.11 illustrates how 64 and 256 sampling points differ in terms of their resolution.

2.8.4 Number of Sweeps (Stimulus Repetitions)

The number of sweeps needed for an average AEP is inversely proportional to the SNR and the amplitude of the AEP of interest. As the SNR improves and the amplitude of the AEP increases, the number of sweeps required for testing decreases. In general, the longer the latency of the response, the greater the amplitude (i.e., CERP > MLR > ABR); therefore, the higher up in the central auditory nervous system being tested, the fewer the number of sweeps that will be necessary to adequately view the AEP response. Generally, sweeps of 200, 1000, and 2,000 are needed for CERP, MLR, and ABR, respectively, though some protocols may call for many more and sometimes less. If the SNR is good, the clinician may stop averaging and quickly move

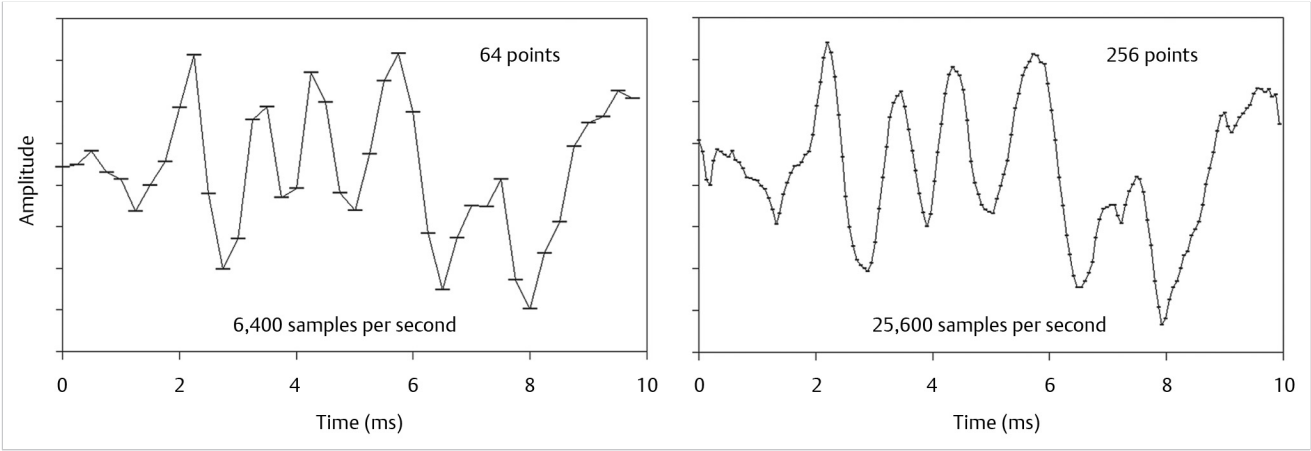

Fig. 2.11 Illustration of 64 (*left*) and 256 (*right*) sampling point differences for auditory brainstem response (ABR) recording. The *short horizontal lines* represent the individual samples, and the *interconnecting lines* represent the waveform that would be produced by the number of sampling points available. Notice the increase in sampling rate resulting from the increase in the number of sampling points. Sampling points of 256, 512, or 1,024 are standard.

on to the next step in the protocol. However, if the SNR is poor, more sweeps are necessary. A technique used often with ABR threshold estimation is Fsp or Fmp, which adds a statistical confidence component to the recordings by helping clinicians decide whether more or fewer sweeps are needed. The technique is described further in Chapters 3 and 6.

2.8.5 Stimulation Rate

The stimulation rate is dependent on the time window as well as the duration of the stimulus, because the goal during AEP testing is to avoid presenting more than one stimuli in the same time window. When there is more than one stimulus in the same time window, the recording will contain overlapping responses and distort the waveform. Stimulation rates are often much slower for later AEPs (e.g., CERPs) than for earlier AEPs (e.g., ECochG and ABR). For example, during ABR testing, the time window is usually 10 milliseconds, and the stimuli are very brief (e.g., 100-microsecond click). Although the clinician could present clicks up to 100 per second for an ABR time window of 10 milliseconds without overlapping responses, the ABR waveform will be severely degraded. During CERP testing, you might have a much longer time window (e.g., 500 milliseconds or 0.5 seconds), and the stimulus you are presenting may be much longer (e.g., 400 milliseconds). In this case, you can present up to a rate of 1.25 stimuli per second. If you present at a faster rate, both the first and second stimuli will occur within the time window, which is not desirable. To increase the stimulation rate, you would have to decrease either the duration of the stimulus or the time window accordingly. If the selected stimulation rate is incompatible with the time window selected, the AEP software will often alert the clinician to this error after the stimulus type and duration have been defined. However, it is best to know the relationship of your stimulation rate, time window, and stimulus duration before selecting your protocol.

Pearl

Associated with stimulation rate are two other terms often seen in the literature: *interstimulus interval* (ISI) and *stimulus-onset asynchrony* (SOA). The ISI is the time duration between the end of the preceding stimulus and the start of the following stimulus. The SOA is the time duration between the start of the preceding stimulus and the start of the following stimulus. When stimuli are long, the SOA will be longer than the ISI.

2.8.6 Filter Settings

Filter settings are employed to eliminate spectral energy (i.e., noise) not contained within the AEP of interest in an effort to maximize the SNR of the recording. Typically, a bandpass filter is used where there is a specified high- and low-frequency cutoff for the recording. Remember that AEPs are nothing more than complex waveforms that can be plotted in both the time and frequency domains. The filter settings employed are simply based on the frequencies that constitute the AEP (i.e., spectral energy). Therefore, filter settings are different for every AEP because the spectral energy or frequency composition of each waveform is different. For example, CERPs are much lower in frequency than the ABR such that bandpass filter settings for a given CERP may be 0.1 to 30 Hz, but those filter settings are changed to 100 to 3,000 Hz for the ABR.

2.8.7 Amplification

Gain is the AEP acquisition feature used to amplify and in turn visualize the recorded response. Refer back to the "Differential Amplification" section earlier in this chapter for information regarding gain settings.

2.8.8 Artifact Rejection

Even with all of the aforementioned measures in place to reduce SNR and suppress noise/signals outside the frequency band of the AEP of interest, artifacts can still make visualization of the AEP response challenging. Therefore, there is an additional acquisition parameter called "artifact rejection," which can be set to eliminate any epochs in which the electrical activity exceeds a predetermined criterion. This is especially helpful for eliminating epochs during which time there might have been excessive movement and/or muscle activity. In some cases, the clinician may want to turn off artifact rejection or set it to more aggressive levels. For example, the vestibular evoked myogenic potential (VEMP) is a myogenic response with high levels of activity. If the artifact rejection is not turned off, most if not all of the responses would be eliminated, rendering the clinician unable to collect enough samples for an averaged response.

Pearl

If noisy recordings persist from electromagnetic noise sources, it may be helpful to explore noise sources in the testing area or around the building using a simple device made of small three resistors (~4.7 kΩ or similar value) and three spare electrode wires.[19] The parts can be purchased easily and assembled together with a little twisting of the wires and mounting the resistors and wires to a sturdy cardboard to act as a simulated head (see ▶ Fig. 2.12). After connecting the wires to the EP system (single channel), hit "Record," and compare ongoing EEG display and averaged recordings at different locations in the testing area. A good testing area should have little to no electromagnetic activity as indicated by reasonably flat averaged recordings and expected EEG display activity.

2.8.9 Electromagnetic Artifacts

In addition to excessive movement/muscle activity, there can be various sources of electromagnetic interference that can obscure waveform collection. The frequency of the electromagnetic artifacts will depend on the source. Power line noise in the United States would present as a 60-Hz cycle noise. Some implanted devices such as pacemakers can create spikes around 100 Hz. And finally, cellphones can also create high-frequency oscillations. Filtering can help eliminate or reduce some of these issues, but when filtering out an artifact that would also serve to filter out frequencies within the AEP response, it becomes necessary to turn off the source or eliminate distance as much as possible. Clearly one cannot do this with a device like a pacemaker, but it is advisable to turn off all unnecessary electronic equipment in the test environment including cellular phones.

2.9 General Subject Factors

Several subject-related factors need to be considered when choosing the most appropriate stimulus acquisition parameters for a given AEP. These subject factors are generally addressed in this section. More information regarding protocol adjustments based on various subject effects for specific AEPs can be found in Section II of this text.

2.9.1 Age

The central auditory nervous system is not fully mature until adolescence. Clinicians need to take maturation effects into consideration, particularly when testing infants and children. For example, the ABR is not adultlike until 18 to 24 months of age. Typically, the most common effects of lack of maturation

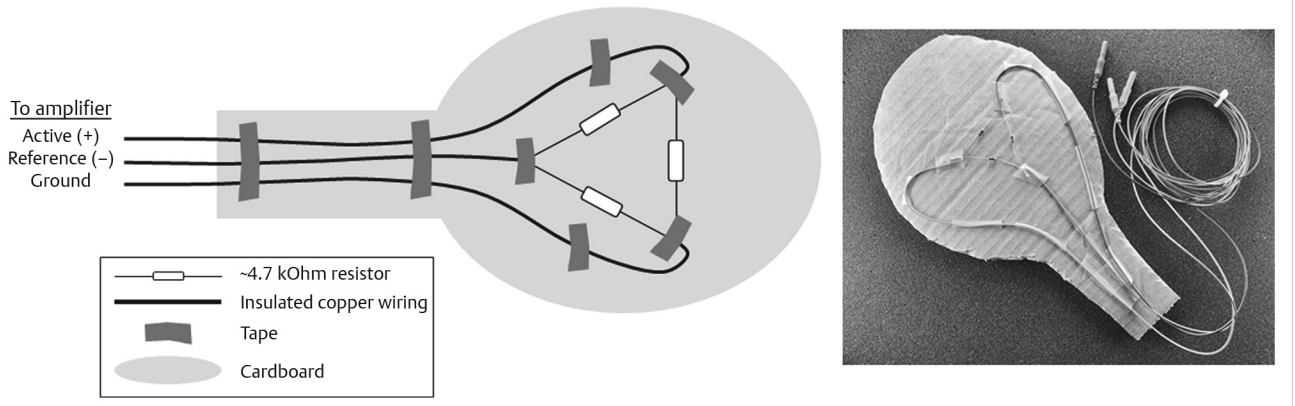

Fig. 2.12 Illustration (*left*) of a simulated head for exploring noisy testing areas made using three ~4.7 kΩ resistors (or similar value), three spare electrode wires, cardboard, and tape. Image (*right*) of the assembled simulated head. (Modified from Luck.[19])

are longer latencies that would call for a longer time window to be chosen. In addition, auditory systems that are either immature or perhaps degenerating are often more negatively affected by faster stimulation rates. In later adulthood, there is typically an age effect on latency for most AEPs such that latency increases slightly with age. Therefore, clinics would be wise to develop age-related normative values.

2.9.2 Gender

Most of the literature with respect to gender effects has centered on the ABR. Specifically, women have shorter latencies and larger amplitude responses than men.[20] Although some researchers have postulated that these are due to differences in head size and scalp/skull thickness, the differences due to these factors are negligible. Others suggest gender differences are related to differences in cochlear anatomy, specifically that the basilar membrane is longer in men than in women. This difference yields longer travel times for acoustic stimuli within the male cochlea, as well as reduced synchronicity of nerve fiber responses resulting from distribution of frequency bands over a longer length.[21]

2.9.3 Muscle Activity

For all AEPs discussed in this text (with the exception of the VEMP), the desired activity is neuronal, not myogenic. Therefore, it is critical to avoid measuring any excess muscle activity, which can obscure the AEP response waveform. Unfortunately, there are many muscles that innervate the head and neck, which can cause problems during AEP recordings. Probably the best known is the postauricular muscle artifact or reflex (PAM or PAMR), which is most problematic during MLR recordings. To reduce muscle artifact contamination, the clinician can alter the electrode montage, choosing an earlobe rather than the mastoid for the site of the active electrode. Another technique to reduce the chances of muscle artifact contaminating the response waveform is to adjust the artifact reject parameter or implement a stricter cutoff criterion if too much artifact seems to be present during recording.

2.9.4 Attention

For many AEPs, attention is not a factor during recording. For example, a patient will be encouraged to relax with eyes closed or sleep during ABR recordings. However, attention plays a larger role in some of the CERPs, particularly the P300 response. Although the clinician does not need to change any stimulus acquisition parameters to account for attention effects per se, the level of attention may have an effect on the morphology of the response. See Chapter 10 for more information regarding the effects of attention on the P300 and other CERP responses.

2.9.5 Temperature

In most instances, temperature will not be a concern during AEP testing. It is only in special circumstances (i.e., during intraoperative monitoring or anesthetization) that body temperature changes should be considered. Certain populations, such as comatose patients and premature infants, are also prone to hypothermia.[22] Because lower body temperature can prolong latencies, it may be advisable to use longer time windows when testing these patient populations.

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