SAMPLE CHAPTER

NEW HANDBOOK FOR AUDITORY EVOKED RESPONSES

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Introduction to Auditory Evoked Response Measurement

Selected principles of electrophysiological measurement, including stimulus and acquisition parameters, test strategies, and patient instructions shared by most auditory evoked responses, are reviewed in this chapter. There is a common perception that AERs are "objective" measures of auditory function, implying that by following a fixed test protocol any tester with minimal technical skills will consistently obtain reliable, valid, and clinically useful data. This is, in fact, a misperception. First of all, it is not possible to follow a fixed and inflexible test protocol and still assess many patients efficiently, effectively, and successfully. Test protocols must often be tailor-made for individual patients. Test protocols are highly dependent on the reason for the assessment. Moreover, because of unpredictable environmental or subject variables, a clinician is frequently required to revise his or her test strategy. To be regularly successful in AER assessment, the clinician must constantly think on his or her feet. The clinician must be prepared to make adjustments in the assessment approach on the basis of clinical judgment and ongoing analysis of data as it is collected during AER recordings. There are myriad interactions among the effects of subject characteristics, stimulus and acquisition parameters, auditory pathology, and other factors on AERs. The complexity of these interactions precludes their prediction or evaluation entirely by computer or the adherence by a clinician to a fixed test sequence. The responsibility for adapting strategy to obtain optimal AER results remains with the clinician. Clinical expertise goes beyond both a superficial "cook book" understanding of AER measurement and extensive "book knowledge" of AER principles. Consequently, interpretation of AERs will probably always be largely dependent on judgment by an experienced clinician. Automated data collection and scoring certainly has assumed an important role in some AER applications, such as newborn auditory screening and neuromonitoring. Automation is even incorporated to some extent into routine AER measurement, for example, with auditory steady state responses (ASSRs). However, automation is not likely to be routinely relied upon for diagnostic clinical AER applications. Perhaps the most dangerous consequence of the assumption that AERs are "objective tests" is an oversimplification of the complexity of clinical assessment and a false sense of security about one's ability to carry out the testing. Consistency in test instrumentation and protocol is always desirable, but should not and cannot be maintained at the expense of test feasibility, efficiency, or accuracy. Major components of the AER evaluation will now be reviewed.

AER MEASUREMENT WITH PATIENTS IN THE REAL WORLD

To reiterate a theme stated at the outset of this book, AER measurement is technically and clinically challenging. Ideally, the audiologist or clinical neurophysiologist first develops a firm grasp of the principles underlying AERs, and then begins to develop necessary technical and clinical skill by recording responses from dozens of normal persons under optimal measurement conditions. Ideal subjects are friendly, cooperative, healthy young adults who are known to have normal hearing sensitivity and auditory CNS function. The test setting is a quiet and familiar clinical facility. There is a relaxed atmosphere, with virtually unlimited test time and no demand for an interpretation and a report of findings. Technical mistakes may not be detected until after the test or, blissfully, not at all. In either case, no harm is done.

Contrast this relatively serene description with one of the following, and not atypical, clinical scenarios.

- A restless newborn infant with suspected peripheral and/or central auditory dysfunction undergoes ABR measurement in an intensive care nursery late on a Friday afternoon. The procedure must be repeatedly halted because of excessive electrical interference from the incubator and physiologic monitors or an ambient noise level that forces the testers to literally shout in order to communicate. The infant's parents are waiting anxiously in an adjacent room.

After a two-month hospital stay beginning at birth, the parents are looking forward to the infant's discharge as soon as "hearing testing" is complete. The attending neonatologist has asked to be paged and informed of the findings as soon as possible.

- ABR assessment is requested for a 9-month-old child with bilateral congenital aural atresia and possibly maximum conductive hearing loss in each ear. The surgeon needs to verify sensorineural auditory status for each ear in order to plan otologic management. If the hearing loss is, indeed, conductive bilaterally, surgery is indicated. If either or both ears have sensorineural component, surgery is contraindicated. The assessment is completed in the operating room under general anesthesia immediately before high-resolution temporal bone CT scanning. About 45 minutes are allotted for the ABR assessment. Again, the physician wants a prompt report of findings. The family is from a distant city, and he will discuss the management plan with parents immediately after the ABR and CT scan so that they can leave for the airport and return home. The outcome of the ABR assessment will largely determine the surgical management approach.
- ABR assessment is carried out in the clinic for neurodiagnosis with an adult having an asymmetric sensorineural hearing loss. The patient understands that the procedure is being performed to rule out a tumor involving the auditory nerve and is understandably anxious and tense. Waveform morphology is poor, in part because of muscular artifact. Pure tone audiometry showed bilateral high-frequency sensorineural hearing impairment and, as recording begins, a wave I component cannot be recorded from either ear. There is an interaural wave V latency difference, but could it be consistent with the difference in hearing sensitivity between ears? The patient is scheduled to return to the neurotologist the same day after the testing, with ABR waveforms and a report in hand.
- Repeated attempts to obtain valid behavioral audiometry findings from a 7-year-old mentally retarded child with Down syndrome have failed, and AERs are requested. Not unexpectedly, middle ear dysfunction is suspected. Sedation is required. Chloral hydrate is administered, but the child actually becomes more active and testing is aborted. What next steps will lead toward successful auditory assessment?
- Combined ECochG/ABR intraoperative recordings are requested to monitor eighth nerve and auditory brainstem function during surgical removal of a moderate-sized meningioma from the cerebellopontine (CP) angle. One objective of surgery is hearing preservation. Preoperative ABR assessment failed to show a distinct wave I on the involved side. In the OR on the day of surgery with this case, AER measurement is made more difficult by excessive electrical artifact. The neurotology-neurosurgery team is expecting moment-to-moment information on functional status of the auditory system as well as information that will be useful in predicting postoperative hearing outcome. How can high-quality AER waveforms be quickly and reliably recorded intraoperatively under these hostile conditions?
- AER assessment in the ICU is requested for a comatose young adult within 24 hours after severe head trauma. The patient is unresponsive to any sensory stimulation. Brain death is suspected. The organ transplant team has been consulted and has already initiated the initial contact with the patient's family. CT scanning showed evidence of unilateral temporal bone fracture as well as diffuse cerebral edema. Medications at the time of testing include sedatives, chemical paralyzing agents, and aminoglycoside antibiotics. The patient is hypothermic. The referring physician requires an immediate report of the findings. What possible influences do the temporal bone fracture, medications, and temperature have on ABR and AMLR outcome? When are AER findings compatible with brain death?
- An ABR assessment of a 2-year-old girl with severe language delay is conducted in the OR under light anesthesia and immediately after insertion of ventilation tubes. Previous behavioral audiologic assessment yielded inconsistent responses. OAEs were absent, but that was anticipated as the patient had a history of middle ear disease. There is no ABR to click stimulation at maximum signal intensity levels (95 dB nHL). Likewise, there is no response to tone burst stimulation at equipment limits. The parents ask whether their daughter will benefit from amplification or whether she is a candidate for a cochlear implant. How will you fit a hearing aid without an estimation of auditory threshold, and is the child even likely to benefit from amplification?

These are just a few examples of the numerous types of clinical challenges faced regularly in AER measurement. For consistently successful AER measurement, the clinician must master relatively straightforward technical skills, such as proper electrode placement and operation of the evoked response system. The clinician must also continuously adapt to unexpected difficulties in testing. The clinician must apply whatever techniques and strategies seem to be useful in dealing with measurement problems presented by a given patient and test setting. Finally, the clinician must know what AER information is needed and must be guided by one overall objective: to get this AER information if at all possible, often as quickly as possible. In this chapter, commonly encountered problems in AER measurement are cited and clinically feasible solutions presented. Admittedly, this is an inadequate format for presenting strategies for troubleshooting in AER measurement because problems do not always occur in isolation. In fact, they are often multiple and related. Also, AER interpretation is largely a matter of detecting dynamic patterns in waveforms. Measurement problems usually are detected first as some aberration in a waveform. Therefore, whenever possible, measurement problems are illustrated here with actual AER recordings. Valuable information is available clinically from AER data as it is acquired, rather than after the waveform is averaged. Unfortunately, this measurement process cannot be presented in a book format. The emphasis in this chapter is on general problems

and solutions. Measurement difficulties encountered most often in specific responses (e.g., ECochG, ABR, ASSR, and AMLR) or in special AER applications, such as intraoperative and ICU neuromonitoring and newborn auditory screening, or in recording nonauditory evoked responses, are also reviewed in more detail in the chapters devoted to each of these topics. Inevitably, not all of the difficulties that may arise in clinical AER measurement are cited in this chapter. I hope, however, that the principles of AER problem solving reviewed here will also be of value in resolving other unmentioned problems.

AER measurement problems can be divided into two general categories. The first category consists of operator errors. That is, a less than optimal, perhaps totally inadequate, AER is recorded because of a technical mistake. Examples of these types of errors are an improper electrode placement or an incorrect equipment setting. The second type of measurement problem, one related to the subject or the test environment, is often more frustrating and its solution more challenging. This second type of problem may plague AER measurement for the experienced clinician as well as the novice. The author, in recording AERs clinically during the course of the past thirty years, has made each of the operator errors described in this chapter, and then some. He has also faced all of the other problems. As noted in the introduction of the book, clinicians cannot expect to record AERs flawlessly, but should always view their results critically and attempt to detect possible measurement problems during recording. In this way, problems can be solved while there is still an opportunity to obtain valid and adequate AER data, i.e., the patient is still in the clinic and hooked up. Put another way, in clinical AER measurement and in life in general, "all's well that ends well."

PREPARATION AND PRECAUTIONS BEFORE THE TEST

An important ingredient in successful AER assessment is adequate preparation before patient contact. Although the degree of preparation required and its impact on the outcome of AER assessment varies among applications, at least three main concerns should be addressed. First, it is extremely valuable to know what kind of patient is scheduled for assessment and why. There are many questions to be asked. What is the patient's age? Is the patient a newborn (premature or full-term?), a young child or older child, a young adult or older adult? Is the primary objective of testing information on auditory or neurological status? What is the tentative diagnosis or what are the likely etiologies to be ruled out in the differential diagnosis? If a diagnosis is suspected, the reader can refer to other portions of this book and additional reference sources to determine the specific AER findings or pattern of findings that are characteristic of the diagnosis and any special recording problems that might be encountered. Has an AER assessment been carried out before? What did it show and are the results available? Does the referral source want an immediate report on the results? Will the patient be reasonably alert, lethargic, or comatose? Is he or she currently on medications that might affect AERs? Why can't behavioral auditory evaluation techniques be used? If previous behavioral testing was done, what did it show? Does the patient have normal hearing and, if not, what is the type and degree of hearing impairment? Is it likely that sedation will be needed? Are there any contraindications to sedation? Is an order for sedation and, if necessary, additional sedation, available? Who will administer the sedation, and is this person ready?

Second, before the testing is scheduled to begin, it is important to ensure that the necessary equipment and supplies are in place. This determination is, in part, based on the answers to the questions above. For example, are there enough clean electrodes of the proper type or enough disposable electrodes on hand? Is there an adequate supply of tape, abrasive liquid, and conducting paste for electrode application and unused insert ear cushions? If the instrumentation is programmable, are programs for the planned test protocols prepared and accessible? Is there a sufficient supply of data record sheets and report forms? These concerns are especially important for mobile AER assessments away from the evoked response laboratory or audiology clinic, because retrieving even a minor missing item might be very time consuming or even impossible. Special steps may be necessary in preparation for certain AER applications, such as newborn auditory screening and neuromonitoring.

Patient Instructions

With the exception of recordings made in the operating room or intensive care unit, some explanation of the AER procedure to the patient is required. For adults and older children who will be tested without sedation, the explanation is given directly to the patient. The parents or caregiver of infants and younger children also benefit from some description of the upcoming test. Instructions vary in detail for different types of AERs, as noted next. As a rule, the time taken instructing the patient is time well spent. Patients who understand what will be done during the procedure, and what will be expected from them, are less likely to be anxious about testing and more apt to be cooperative and relaxed during testing. Recording AERs is, in many respects, a high-tech procedure. The relatively sophisticated equipment (computer, electrodes, earphones), often in combination with a clinical environment (e.g., white lab coats, austere test room), tend to make the typical patient rather apprehensive. AER assessment may be a familiar and comfortable daily routine for the clinician, but for a patient on the initial visit, it is likely to be foreign and even frightening. The electrodes alone often conjure up scenes of horror. Patients may even incorrectly assume that the electrodes are used to present a shock to their

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head, rather than to passively detect brain activity containing the AER.

The clinician should never forget that there is a person—a human being—between the stimulus transducer and the recording electrodes. Each and every patient deserves a simple, but complete, description, in everyday language, of the AER procedure that is about to be performed. Good clinicians are not only technically skilled in recording AER data, but also sensitive and caring in the approach taken with patients and family members before, during, and after test sessions. Not unexpectedly, some patients undergoing neurodiagnostic assessment have communication impairment secondary to pathologies or disorders, for example, patients with receptive language impairment following a cerebrovascular accident (stroke). Care must be taken to be sure that all patients understand the explanation of the nature of the AER assessment and specific instructions.

It is always helpful for clinicians to put themselves in the patient's or family member's shoes before the test. Often these people are already anxious about the possibility of a health problem, ranging from a hearing impairment to a brain tumor. Perhaps they have traveled many miles. Patients from a rural area may have been frightened by urban traffic and may have had difficulty finding a parking space or may have become lost in a medical center maze. Parents of young children may be worried about possible dangers of sedation or that the testing will be painful to their child. Any patient may, of course, have concerns about the cost of procedure and whether insurance will cover this cost. New clinicians will become sensitized to potential patient concerns about evoked response assessment by undergoing AER measurement themselves. Actually, the clinician can learn much about recording techniques by practicing (behind closed doors) AER measurement while serving as both the subject and the tester.

Some guidelines on patient instructions are offered below for each major AER. For patients who, during their first visit to the clinic, are scheduled to return for AER assessment, a brief explanation of the scheduled test procedure may reduce anxiety. Simply written summaries of these instructions may also be given to patients at that time, mailed before the test, and or handed to the family when they arrive on the AER test date. Many clinics and centers now include on their website patient information about test procedures, diseases, and disorders, as well as clinical services offered at the facility.

GENERAL EXPLANATIONS. | Some patient instructions are appropriate for all types of AERs, whereas others are uniquely suited for one type of AER or another. The common features of AER patient instructions are discussed here, while details specific to each AER follows. The detail and vocabulary of instructions will vary depending on the age and educational background of the patient or family member. Two fundamental components of patient instructions are (1) what procedure will be performed and (2) how it will be done. In many cases, some mention of why testing is being done is also in order, although this latter information is optional and dependent on the objectives of testing—for example, hearing threshold estimation versus neurodiagnosis. A rather typical explanation for ABR procedure is as follows:

> In this test, I [or we] will record a response from your ear, a response of the nerve that runs from your ear to your brain, and even brain waves caused by sounds. [The phrases auditory evoked response, auditory brainstem response, and other technical terms are used only with patients having some knowledge of the procedures or medical terms in general.] The response from your ear and the brain waves will be picked up with these wires. The wires will be taped onto your head and ears. You will hear clicking sounds [or beeping tones] through these earphones. They sound like this [click your tongue]. You do not have to listen to these sounds. I just need for you to lie here very quietly. Try to stay relaxed and to keep your jaw loose. We'll recline this chair just before the test begins. It's OK if you fall asleep [for ECochG and ABR; see specific instructions below for AMLR, ALR and P300]. In fact, we'll turn down the lights when the test begins to help you to rest and maybe fall sleep.
>
> First, I will scrub the skin on your forehead and earlobes (or the outer part of your ear canal) with a scratchy liquid. This is the most uncomfortable part of the test. Then, I'll put some paste on these wires [electrodes] and tape them to these locations. I'll clean the paste off your skin when we are done with the test. During the test, you will wear these earphones or [for inserts] I will place these soft foam plugs in each of your ears. This test may give us (or whoever referred the patient) important information on your hearing.

ECochG. | Much information explained to patients is similar for all AERs, as noted above. Instructions specific to ECochG depend mostly on electrode type. If earlobe electrodes are

Important points to be clarified for each patient:

- AER recording is a routine clinical procedure, used even with newborn infants.
- The procedure does not pose any risk to the patient.
- The procedure is noninvasive and not painful (ECochG may be an exception).
- There are no side effects for unsedated AER recordings.
- Results may not be immediately available.
- The assessment can be stopped at any time upon patient request.

used, ABR instructions apply as well for ECochG. With ear canal electrodes, the patient is told that the outer portion of the ear canal will be scrubbed lightly with a scratchy liquid. Then, a soft foam plug will be placed within this portion of the ear canal. Note that a patient's hearing will be attenuated by about 20 dB after the foam plugs are inserted in the ear canal, and the tester may need to speak very loudly to be heard. If a tympanic membrane electrode type is used (typically without anesthesia), the patient is told that a soft plastic tube will be inserted into the ear canal. The patient will feel the tube within the ear canal. During insertion of the electrode the patient might experience a tickling feeling, and it may be slightly uncomfortable. The patient will have a sensation of pressure or fullness when the soft flexible end of the tube rests on the eardrum. The patient is encouraged to tell the tester what the electrode feels like, especially if it is too uncomfortable. Transtympanic electrode instructions, of course, are slightly different. Following the general instructions just noted, the patient is told that the doctor (physician) will numb the eardrum with a liquid (e.g., Phenol). This may cause a stinging sensation. It is the most uncomfortable part of the test. Then the doctor will place an electrode into the ear canal and through the eardrum. Finally, a foam plug will be inserted gently into the ear canal. At this point in the instructions, the typical patient will no doubt appreciate an estimate of test time. Generally, after electrode placement, transtympanic ECochG can be completed in less than 10 minutes. The foam plug and needle electrode will be removed as soon as testing is completed. There should not be any discomfort after testing. The author, who has acquired ECochG experience with this electrode type, has not yet encountered a patient who has refused to undergo the procedure or who complained of excessive discomfort during the procedure. Patients, in fact, occasionally fall asleep during testing and often do not realize when the electrode is extracted from the tympanic membrane.

ABR. | The general instructions cited above are sufficient for most patients undergoing ABR assessment. Adults and children are encouraged to sleep during the test. Sleep is facilitated by making the patient comfortable (stretched out with a pillow under the his head) and by lowering lights in the test room. Administration of sedation (usually chloral hydrate) to induce sleep is often indicated with children between the ages of 3 to 6 months and 6 years (see Chapter 8). Sedation is occasionally helpful as well for tense adults, although another drug (e.g., Valium) is typically used. With any AER assessment, patients usually rest in the supine position on a gurney or bed. It may be necessary to ask how the patient can be made more comfortable. For example, readjusting the pillow under the head may serve to relax the neck muscles and promote sleep. The patient may wish to remove his or her eyeglasses and shoes. Also, men may wish to loosen their ties and women may want to remove earrings. If the test room is cool, a blanket is useful to keep the patient comfortable and to maintain normal body temperature. Low body temperature (hypothermia) may influence ABR findings (see Chapter 7). Finally, patients should be given the opportunity to visit the restroom before electrodes are applied and testing begins (and after to freshen up).

AMLR. | Encouraging a relaxed state is very important for quality AMLR recordings. Post-auricular muscle (PAM) artifact, which can seriously interfere with identification of AMLR components (see Chapter 11 for details), is more likely with tense patients. The challenge in AMLR measurement, however, is to maintain a relaxed patient state without necessarily allowing the patient to fall asleep. Sleep may reduce AMLR amplitude, and changes in sleep status during testing contribute to variability in findings. If the choice facing the tester is a tense versus sleeping patient, quality of waveforms is more likely to be enhanced by sleep. Naturally, in describing electrode placement to the patient, the tester should mention also that an electrode may be placed on the scalp (and in hair) on each side of the head.

ALR. | Either an awakened patient (for adults) or a deep sleep state (for infants and young children) is essential for optimal ALR measurement conditions. Again, the challenge is to keep the patient awake while also encouraging the patient to relax. The patient is asked to rest comfortably, but not to fall asleep. Usually, it is best for the patient to lie still with eyes open. Also, arranging for the patient to view silent video material (e.g., cartoons or movies with subtitles) is helpful in facilitating a quiet yet awake state of arousal. A number of investigators have described in their protocols for recording late latency AERs the use of videos or DVDs to maintain an awakened state for pediatric and adult patients. While AERs are recorded, the patient watches a cartoon or movie, with the audio either at a low volume or muted. The tester still should periodically assure that the patient has not fallen asleep. As noted in the section on test strategy above, the proper patient state for each AER when recorded as part of a test battery may be facilitated by the following sequence: ALR, P300, AMLR, and ABR/ECochG. This is based on the premise that the patient will begin the testing alert, and then will tend to fall asleep as the testing continues.

P300. | Patient instructions are typically an extremely important component in successful P300 measurement. Whenever possible, the patient must clearly understand the attention-related task, if attention is required for the P300 recording. For example, the patient may be told that there will be two kinds of sounds, one with a lower pitch and the other with a higher pitch. He or she will hear the lower pitched sound quite often, but will occasionally hear the higher pitched sound. The task is to listen carefully for the occasional higher pitched sound, and to count how many of these sounds he or she hears during the test. The patient will be asked to report

the number of these sounds at the conclusion of the test. Of course, throughout the test the patient should remain alert and not doze or fall asleep. A passive P300 response (P3a) can be recorded without the requirement of subject attention to the stimuli, as reviewed in Chapter 12.

STIMULUS PARAMETERS

Acoustic stimuli are necessary for generation of all AERs. Stimulus properties, such as frequency, duration, intensity, rate, and polarity, exert profound and often interrelated effects on AER measurement. There are, in addition, complex interactions among some stimulus factors and subject characteristics (e.g., age, cochlear hearing impairment). Equally important is the transducer that converts an electrical signal into the acoustic signal that elicits the response. Further, mode of stimulus presentation, such as monaural versus binaural, may also affect the response that is recorded. Finally, the presence of masking sounds affects auditory response. Proper stimulus selection, definition, calibration, and presentation is one of the most challenging, yet essential, aspects of AER measurement. General stimulus factors in AER measurement are reviewed in this chapter. Three simple principles important for all auditory evoked responses are stated in Table 3.1. Terminology used in reference to acoustic stimuli is defined briefly throughout the chapter. However, the reader without background in psychoacoustics and hearing science will require additional information, available from numerous textbooks as well as on the Internet.

TABLE 3.1. Three General Principles of AER Measurement

Stimulus Principle

- The optimal stimulus rate for an AER is directly related to the speed of the response.
- Early AERs (e.g., ECochG and ABR) are fast responses that can be elicited with faster stimulus rates, whereas later AERs (e.g., AMLR or P300) are slower responses that require slower stimulus rates.

Filter Principle

- Elimination of unwanted electrical activity (noise) with preservation of desired electrical activity (response).
- Early AERs (e.g., ECochG and ABR) are fast responses with more high-frequency content, whereas later AERs (e.g., AMLR or P300) are slower responses with more low-frequency content.

Averaging Principle

- The extent of signal averaging (time) needed to record a detectable AER depends on the size of the signal (the AER) and the amount of noise (electrical and myogenic) within the recording (the signal-to-noise ratio, or SNR).
- Early responses have smaller amplitude and require more averaging, whereas later responses have larger amplitude and require less averaging (when noise is constant).

Stimulus Type and Frequency

For neurophysiologic reasons, early latency AERs are recorded optimally with very brief (transient) stimuli having an almost instantaneous onset. In fact, the rapid onset of the transient stimulus is important in producing the synchronous firing of numerous auditory neurons that underlies these responses. Therefore, the brief duration (e.g., 0.1 ms or 100 μsec) click, which has an abrupt onset, is by far the most commonly used stimulus for ECochG ABR measurement. The click stimulus may actually be one of several somewhat different acoustic signals, including a rectangular voltage electrical pulse, diphasic square-wave pulses, triangular waves, or a single period of a high-frequency haversine or half-sine wave. Terminology used in describing electrical signals and acoustic stimuli in AER measurement is defined in Table 3.2. Selected types of stimuli (click, tone, burst) that may be used in AERs are illustrated in Figure 3.1. An abrupt signal, such as a rectangular electrical pulse, has a very broad spectrum and, when delivered to a transducer, results in an acoustic signal encompassing a wide range of frequencies. In theory, then, this range of frequencies activates the cochlea and, specifically, the hair cells, over an extensive region of the basilar membrane. The frequency content of the stimulus actually generating the AER for a given subject, however, depends on a variety of factors, such as (1) stimulus intensity, (2) the electro-acoustic properties of the transducer, (3) ear canal and middle ear properties affecting sound transmission, and (4) the integrity of the cochlea.

Higher frequencies in the click acoustic spectrum are responsible for generating the ABR in the normal ear. An ABR evoked by a moderately intense (e.g., 60 dB nHL) click stimulus and delivered with insert earphones reflects activation of the high-frequency regions (roughly 1000 through 4000 Hz) of the cochlea. Reported differences in the frequency region most important for generation of the ABR (such as 1000 to 4000 Hz, 4000 to 8000 Hz, 3000 Hz, 4000 Hz, 2000 Hz and above, and so forth) are probably, to a large degree, due to the differences in stimulus intensity and the upper frequency limit of the acoustic transducers used in the studies to present the clicks (Bauch & Olsen, 1986; Coats, 1978; Coats & Martin, 1977; Eggermont & Don, 1980; Gorga, Reiland, & Beauchaine, 1985; Gorga, Worthington, Reiland, Beauchaine, & Goldgar, 1985; Hoke, Lutkenhoner, & Bappert, 1980; Jerger & Mauldin, 1978; Kileny, 1981).

More apical (low-frequency) regions of the cochlea are also activated by the click but, for two reasons, do not

TABLE 3.2. Definition of Terms Used to Describe Auditory Evoked Response (AER) Stimulus Characteristics

TERM	DEFINITION
air conduction	The process by which sound is conducted to the inner ear (cochlea) through the air in the external acoustic meatus (ear canal) as part of the pathway.
alternating	The polarity of the stimulus pressure wavefront is alternated on successive trials (between rarefaction and condensation).
bone conduction	Transmission of sound to the inner ear mediated primarily by mechanical vibration of the cranial bones.
brief tone[a]	A tone pulse with a duration of less than 20 ms.
click	Acoustic signal produced by a rectangular electric pulse of a specified duration, delivered to a transducer.
condensation	A stimulus polarity that initially causes the pressure wavefront of a transducer to move toward the eardrum.
filtered click	Acoustic signal produced by a rectangular electric pulse of a specified duration, passed through a filter, and subsequently delivered to a transducer.
gating function	The time function that modulates the amplitude of a continuous signal in order to determine the turn-on and turn-off characteristics.
hearing level (HL)	For a specified stimulus, for a specified type of transducer, and for a specified manner of application, the HL is the SPL, or the vibration force level, of the signal set up by the transducer with a specified coupler minus the appropriate reference equivalent threshold level for air and bone conduction, as applicable. It is measured in decibels (dB) relative to a standard reference threshold for the specified stimulus.
masking	The process by which the threshold of audibility of a signal is raised by the presence of another sound.
peak sound pressure	The peak sound pressure for any specified time interval is the maximum absolute value of the instantaneous sound pressure in that interval. The reference for 0 dB peak sound pressure is 20 μPa (micropascals).
peak-to-peak equivalent sound pressure level (peSPL)[a]	The peSPL of a short-duration signal is the sound pressure level calculated as (RMS) of a pure tone, which, when fed to the same transducer under the same test conditions, has the same peak-to-peak amplitude as the short-duration signal.
plateau duration	When measurable, this is the time during which the envelope of the burst is at 100% amplitude.
polarity	The initial direction of the pressure wavefront in the stimulus waveform, measured at the face of the transducer.
rarefaction	A stimulus polarity that initially causes the pressure wavefront of a transducer to move away from the eardrum.
repetition rate	The number of stimuli presented per unit time.
rise/fall times	The time interval for a waveform to go from zero amplitude to maximum amplitude (rise time) or from maximum to zero (fall time).
sensation level (SL)	The level of the sound above its threshold of audibility for an individual subject.
sound pressure level (SPL)	Based on a physical reference for the (RMS) sound pressure. For any sound, it is equal to 20 times the logarithm to the base 10 of the ratio of the pressure of the sound to the reference pressure. The typical reference for 0 dB RMS SPL is 20 μPa.
tone burst	Specifiable carrier frequency with a specified envelope function by which the carrier is modified.
total duration	The time between each instance of zero amplitude on the waveform envelope.
white noise	A noise for which the spectrum density is substantially independent of frequency over a specified frequency range. The slope of the pressure spectrum level of white noise is 0 dB per octave.

[a] From Working Group 10 (Specification of Reference Audiometric Test Signals of Short Duration).

Source: The first draft of American National Standard entitled "Stimulus Specifications for Instruments Used to Measure Auditory Evoked Potentials" and proposed by the Acoustical Society of America Accredited Standards Committee, Working Group S3–72, Measurement of Auditory Evoked Potentials. Courtesy of Chair: R. A. Ruth.

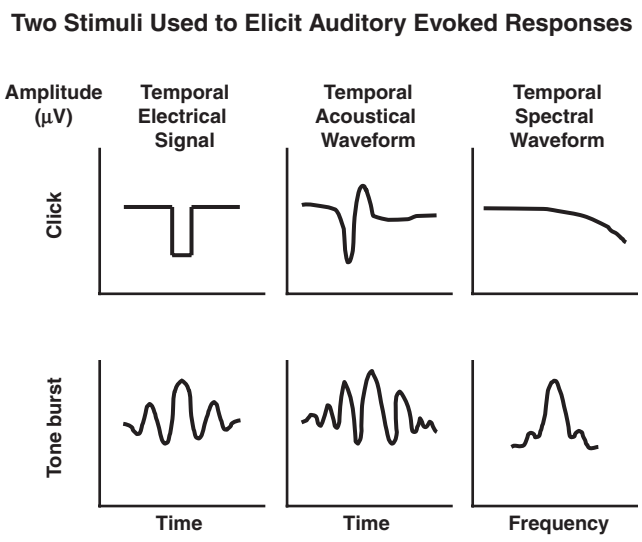

FIGURE 3.1. Two types of stimuli (clicks and tone bursts) used to elicit auditory evoked responses.

contribute much to the ABR, at least in normal hearers. First, the neurophysiologic response elicited by cochlear activation in the higher frequency regions (near the base of the cochlea) has already occurred by the time the traveling wave reaches the apex and has activated hair cells in this region. Second, the leading "front" of the traveling wave is more gradual (less abrupt) when it reaches the apical region and consequently not as effective introducing synchronous firing of many eighth-nerve afferent fibers over a concentrated portion of the basilar membrane. Instead, smaller numbers of afferents sequentially fire over a more dispersed stretch of the basilar membrane. In persons with an impairment of auditory sensitivity for the higher frequency region, generation of the ABR may not necessarily follow this pattern. In addition, the portion of the cochlea contributing to the ABR varies as a function of the components (e.g., wave I vs. wave V) and stimulus intensity. For example, wave I appears to reflect basal activation, whereas wave V may reflect activity from portions of the basilar membrane closer to the apex. Also, at high stimulus intensity levels, there is spread of activation toward the apex, whereas at lower intensity levels, activation is limited more to the basal region.

There are, therefore, two general principles to keep in mind in considering stimuli for evoking auditory responses. First, frequency specificity of a stimulus (i.e., the concentration of energy in a specific frequency region) is indirectly related to duration (Burkard, 1984; Gabor, 1947; Gorga, Reiland, & Beauchaine, 1985; Harris, 1978). With very brief stimuli, energy tends to be distributed over more frequencies, whereas stimuli with longer duration (including rise/fall times and plateau time) are spectrally constrained. Second, there is generally a direct relationship between duration of the response and duration of the stimulus. That is, slower responses (longer latency) are activated best by slower (lower rate of stimulation, and longer onset and duration) stimuli whereas faster (shorter latency) responses require faster (higher rate of stimulation and shorter onset and duration) stimuli.

Duration

Stimulus duration is the sum of the rise time, plateau time, and fall time. These terms were defined in Table 3.2 and are illustrated in Figure 3.2. This definition is actually oversimplified, primarily for illustrative purposes. Duration for the electric waveform used in generating the stimulus can be determined by means of an oscilloscope. Duration of the acoustic waveform of the stimulus also can be measured with an oscilloscope, along with a standard coupler and a sound level meter. Whether measurements of duration are made electrically or acoustically, a consistent definition must be used. Other examples of definitions for rise/fall times are the time interval from the onset of any amplitude to maximum amplitude, the time interval between the 10 percent and the 90 percent amplitude points, or the number of cycles of a sinusoidal stimulus occurring during the rise or fall portion of the stimulus. Plateau time likewise can be described in different ways, such as the time interval between the 50 percent amplitude points on the rise versus the fall envelopes of the stimulus or simply the time from one end of the plateau to the other for the click. Both rise/fall times and plateau time were incorporated into the concept of "equivalent duration," defined by Dallos and Olsen (1964) as two-thirds of the rise time plus the plateau duration.

There are two common approaches for classifying tonal stimuli based on their duration characteristics. One is to define a constant rise time for all nonclick stimuli. For example, Stapells and Picton (1981) suggest that tonal stimuli at any frequency consistently have a 5 ms rise time. Kodera, Yamane, Yamada, and Suzuki (1977) and by Klein (1983)

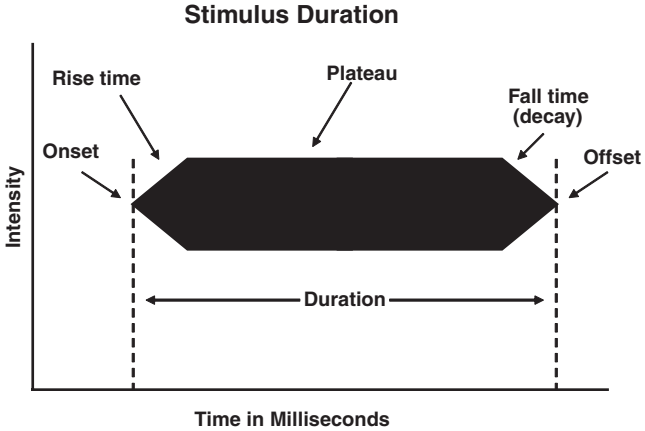

FIGURE 3.2. An illustration of stimulus components that contribute to duration, including rise time, plateau, and fall time.

employed the constant rise-time approach. With a fixed rise/fall time, temporal features of the stimulus are clearly constant, but spectral splatter will be greater for lower versus higher frequencies. The other approach, introduced by Hallowell Davis and colleagues (Davis, Hirsh, Popelka, & Formby, 1984) and recommended also by others (Coats, Martin, & Kidder, 1979; Hall, 1992) is to define tone-burst rise-time duration on the basis of a constant number of cycles. Specifically, Davis suggested using tones with rise and fall times of 2 cycles and a plateau of 1 cycle. This is referred to as the 2-1-2 paradigm for stimulus duration. Because 1 cycle for a 1000 Hz tone (i.e., by definition 1000 cycles per second) lasts 1 ms, the 2-1-2-rule would define a tone burst with rise/fall times of 2 ms and a plateau of 1 ms. A 500 Hz stimulus, with cycles each lasting 2 ms (i.e., 1000 ms/500) would, by the 2-1-2 rule, have rise-plateau-fall values of 4 ms–2 ms–4 ms, and so on. As described in Chapter 8, the most common current duration of tone bursts used now for frequency-specific ABR measurement is 2 cycles for the rise and fall times and no (0 ms) plateau. With this approach, duration features of various stimulus frequencies vary, yet energy is held constant for different frequencies.

Complex interactions among stimulus parameters influence AER recordings. Stimulus duration is particularly closely related to the frequency content of the stimulus and to the rate and interstimulus interval (ISI). Duration inversely affects spectral (frequency) content. For stimuli of extended durations, frequency content may consist of a single pure tone. In critically reviewing studies of stimulus duration and AERs, and also in attempting to define the clinical implications of altering stimulus duration, it is always reasonable to question whether changes in AERs that appear to be due to duration are, in fact, a result of a broader stimulus frequency content. This concern is enhanced for patients with auditory pathology. The connection between stimulus duration, stimulus rate, and interstimulus interval can be understood intuitively. If a certain number of stimuli are presented within a specific amount of time, such as 20/sec, then increasing the duration of each stimulus while keeping the number constant (e.g., at 20) will result in decreased interstimulus intervals. Alternatively, increasing the number of stimuli presented within 1 second will, of course, increase the rate and decrease the interstimulus intervals. Duration (rise/fall and plateau times) is first reviewed as a factor in AER measurement, followed by a discussion of stimulus rate and interstimulus interval.

Intensity

As a general principle, AER latency decreases and amplitude increases with greater stimulus intensity. The physiologic bases for the intensity versus response relations were reviewed in Chapter 2. Effects of intensity on AERs have probably been studied more than those of any other stimulus parameter. Intensity does not necessarily affect all AERs in the same way and does not produce simple linear effects, even for a single AER (e.g., ABR), or equivalent effects for both latency and amplitude. Also, intensity often interacts in a complex fashion with a variety of subject characteristics and other stimulus parameters. Terms use in describing intensity were defined in Table 3.2. The unit of measure for intensity is the dB (decibel). A full discussion of the dB is beyond the scope of this book. As many as five references may be used to describe stimulus intensity in AER measurement:

1. dB sound pressure level (SPL)
2. dB peak-equivalent SPL (peSPL)
3. dB hearing level (HL) (according to ANSI standards)
4. dB sensation level (SL)
5. dB normal hearing level (nHL).

The most common convention clinically is to define intensity with a biological or behavioral reference, that is, in dB relative to the normal behavioral hearing threshold level for the stimulus, e.g., click or tone burst, usually indicated as "dB nHL." Threshold level for the click stimulus (i.e., the intensity level on the evoked response system at which the click is just audible [detectable]) is determined in a clinical facility (where the AERs will be recorded with patients) for a group of ten to fifteen normal-hearing young adults. The average of these threshold levels, in dB, is referred to as 0 dB nHL and is the reference level for indicating clinical intensity level. For example, if the average dB level for detection of the click by the normal subjects was 5 dB, then a dial or screen setting (equipment setting) of 75 dB would actually correspond to 70 dB nHL (75 minus 5 dB). It is important to keep in mind, as noted in the next section on stimulus rate, that faster click rates will enhance behavioral hearing levels, so at a high rate (e.g., 70 or 80 per second) the click threshold will be about 5 to 6 dB lower (better) than at a slow rate (e.g., 5 to 10 per second).

Another intensity reference sometimes reported in AER studies, and commonly used in hearing science, is dB SPL. The reference for 0 dB SPL is typically 0.0002 dynes/cm^2, or 20 microPascals (μPa). Devices for measuring dB SPL often cannot capture rapid onset, short-duration AER stimuli, such as clicks. A common practice, therefore, is to describe the peak sound pressure of these stimuli in terms of dB SPL for pure-tone stimulus. The peak of the click voltage waveform on an oscilloscope is compared to the peak for a long-duration pure tone of known intensity in dB SPL and is referred to as peSPL (peak equivalent SPL). The equivalent of 0 dB nHL under typical stimulus conditions (a 0.1 ms click presented at a rate of about 10 to 20 per second with conventional audiometric earphones) is 36.4 dB peak SPL and 29.9 dB peSPL (Burkard, 1984; Klein & Teas, 1978; Stapells, Picton, & Smith, 1982).

Rate

Rate is a stimulus parameter that must be selected by the operator in AER measurement. Therefore, an understand-

ing of the effects of stimulus rate is needed to make rational decisions regarding which rate to use for different types of AERs and for different clinical applications. In the hands of an experienced clinician, stimulus rate can be manipulated to permit the fastest data collection in the least amount of time, thus either saving test time or permitting a thorough AER assessment in the time available (e.g., while a small child sleeps after sedation). There is no single correct rate, one that is appropriate for all patients under all test circumstances. The effects of rate are distinct for each of the AER types, particularly the shorter (ECochG, ABR) versus longer (ALR, P300) responses. For each AER type, rate effects are a product of the interactions among rate, a variety of subject characteristics (such as age, body temperature, and drugs), and various other stimulus parameters (such as intensity and duration). Finally, rate appears to be a factor in the diagnostic power of certain AERs. That is, rate may interact also with neuropathology.

A simple, yet statistically and clinically significant relationship exists between rate for transient stimuli and behavioral auditory threshold. From a stimulus rate of 5/sec to a stimulus rate of 80/sec, threshold is enhanced by 5 dB (measured in peak SPL). Presumably, this is due largely to temporal summation of acoustic energy, similar to the effect of increasing acoustic stimulus duration, although other processes are likely involved and the effect has not been consistently demonstrated (Klein & Teas, 1978; Picton, Oulette, Hamel, & Smith, 1979). The rate-versus-intensity relation itself is in turn influenced by frequency. Significantly less threshold improvement with increasing rate is observed for high- versus low-frequency stimuli. Stimulus rate must be considered in collecting normative AER data.

Interstimulus Interval (ISI) and Rate

For transient (very brief) stimuli, the interval between successive stimuli can be determined by dividing a discrete time period by the number of stimuli presented within that period (i.e., 1 second/rate = ISI). If a transient stimulus, for example, is presented at a rate of 20/sec, the accumulated time of the actual stimulus presentation is negligible. A total of 1000 ms (i.e., 1 second) divided by 20 results in an ISI of 50 s. With a rate of 10/sec, the ISI is 100 ms; for a 100 stimuli/second rate, the ISI is 10 ms, and so forth. For nontransient stimuli, calculation of ISI is not as straightforward because duration times for each individual stimulus accumulate and consume some of the time. If total duration of each stimulus is 5 ms (2 ms rise and fall times plus a 1 ms plateau), then for a rate of 20 stimuli/second, the accumulated stimulus time is 100 ms (20 stimuli at 5 ms each). Within a 1 sec (1000 ms) time frame, therefore, only 900 ms are available for the ISIs. Thus, 900 ms/20 yields an ISI of 45 ms. Analysis time could not be greater than this without including the response from the subsequent stimulus presentation within the same time period. If stimuli are presented at such a rapid rate that they occur within the analysis period, they will not contribute to the response and can actually degrade the averaged response.

Fast responses, such as the ECochG or ABR, occur within a relatively brief time period (5 to 6 ms or less), require relatively brief ISIs, and permit more rapid stimulus rates. Slower responses, such as the ALR or P300, last from 250 to 300 ms, require relatively extended ISIs, and limit effective stimulation rate to no faster than approximately 2 stimuli/second. When refractory times are also considered, optimal rate may be as low as 1 stimulus/2 second, or much lower. The effect of ISI on AERs is related to basic neurophysiologic mechanisms. Following every neural event (an AP or a postsynaptic membrane potential), there is a recovery or refractory period during which the neural unit is either incapable of being activated or has a higher threshold for activation. If the ISI time period exceeds this recovery period, then the neural unit can fully recover and will be responsive to the next stimulus. When ISIs are shorter than the recovery period, however, some stimuli will not contribute fully to the response because they are presented during the recovery period for the neural units generating the response. The result may be alteration of the response, such as increased latency or decreased amplitude. Physiologic processes presumably underlying these alterations are variations in the neural refractory period, changes in neural transmission factors, and adaptation and fatigue of neural receptor elements. Among AERs, there are different recovery times and, therefore, different requirements for ISIs. The neurophysiologic events of longer latency AERs, such as the ALR, require longer recovery periods. For example, amplitude of the auditory late response increases with progressively longer ISIs, up to 8 seconds. Onset neurons underlying the ABR, on the other hand, have relatively rapid recovery times. Therefore, even very brief interstimulus intervals (ISIs < 10 ms) are sufficient in measurement of the ABR.

Polarity

There are three categories of stimulus polarity in AER measurement—condensation, rarefaction, and alternating. With a positive electrical pulse or signal and movement of the transducer diaphragm toward the tympanic membrane, a click signal with a positive pressure wave is generated. Movement in a positive direction, or a positive polarity, is also known as "condensation polarity." A pressure wave in a negative direction (negative polarity), produced by a movement of the transducer diaphragm away from the tympanic membrane, is called "rarefaction polarity." Alternating polarity is a switching between condensation and rarefaction polarities at subsequent stimulus presentations. Polarity is an important feature for a click stimulus. Clinically, polarity is not as critical a feature for tonal stimuli. A tonal stimulus, by definition, oscillates in a sinusoid fashion from one polarity to the other.

The polarity (phase) of the initial portion of a tone stimulus may also play a role in AER measurement.

An understanding of some basic principles of cochlear physiology is required to appreciate the effects of click polarity on AERs, especially ECochG and ABR (see also Chapter 2). According to different investigators (Brugge, Anderson, Hind, & Rose, 1969; Dallos, 1973; Davis, 1976b; Tasaki, 1954; Zwislocki, 1975), the afferent auditory nerves are activated primarily by the portion of a stimulus that moves the basilar membrane upward, in the direction of the scala vestibuli. This cochlear activity occurs when a rarefaction (negative) polarity or phase stimulus is presented, theoretically producing an outward movement of the tympanic membrane and in turn the stapes footplate in the oval window (Figure 3.3). With the resultant basilar membrane deviation upward toward the scala vestibuli in the cochlea, stereocilia on the hair cells in the organ of Corti are bent in the direction of the tallest stereocilia, receptor potentials are produced at the apex of the outer hair cells, and a negative CM is generated in the scala vestibuli while a positive CM is generated in the scala tympani. Bending of the stereocilia on the inner hair cells secondary to the effects of endolymph flow generates a bioelectrical event, synaptic transmission via the neurotransmitter glutamate, and afferent activity in the eighth (auditory) cranial nerve.

The apparently simple relationship between stimulus polarity and cochlear physiology, as just outlined, is complicated by at least four factors:

- Polarity of the stimulus may be reversed by ear-canal acoustics in its course from the transducer diaphragm to the tympanic membrane and/or by middle ear or inner ear mechanics in its transformation from eardrum to hair cell (Borg & Lofqvist, 1982; Dallos, 1975; Gerull, Mrowinski, Janssen, & Anft, 1985). Of course, if stimulus polarity is reversed twice before the afferents are activated (once in the ear canal and again in the middle ear), the original polarity will be maintained.
- The outward (lateral) movement of the oval window (the stapes footplate) with rarefaction clicks may be greater than the inward (medial) displacement due to condensation clicks (Guinan & Peake, 1967), and this polarity difference may be intensity dependent.
- Polarity effects are probably not comparable for conventional rectangular-wave clicks (with almost vertical onset and offset) versus for clicks with rapid onset but gradual offset. Clicks with rapid onset and offset produce basilar membrane movement in first one and then the other direction (in response first to onset and then to offset), even though polarity of a stimulus is designated by the onset direction.
- The initial component of the acoustic click waveform may be followed by an even larger amplitude and opposite-polarity (phase) second component, which is actually effective in generating the response. Some acoustic transducers "ring" when delivering a transient stimulus, resulting in oscillation and alternating polarities.

TRANSDUCERS

A transducer is a device for converting energy from one form to another. For most AER applications, the stimulus

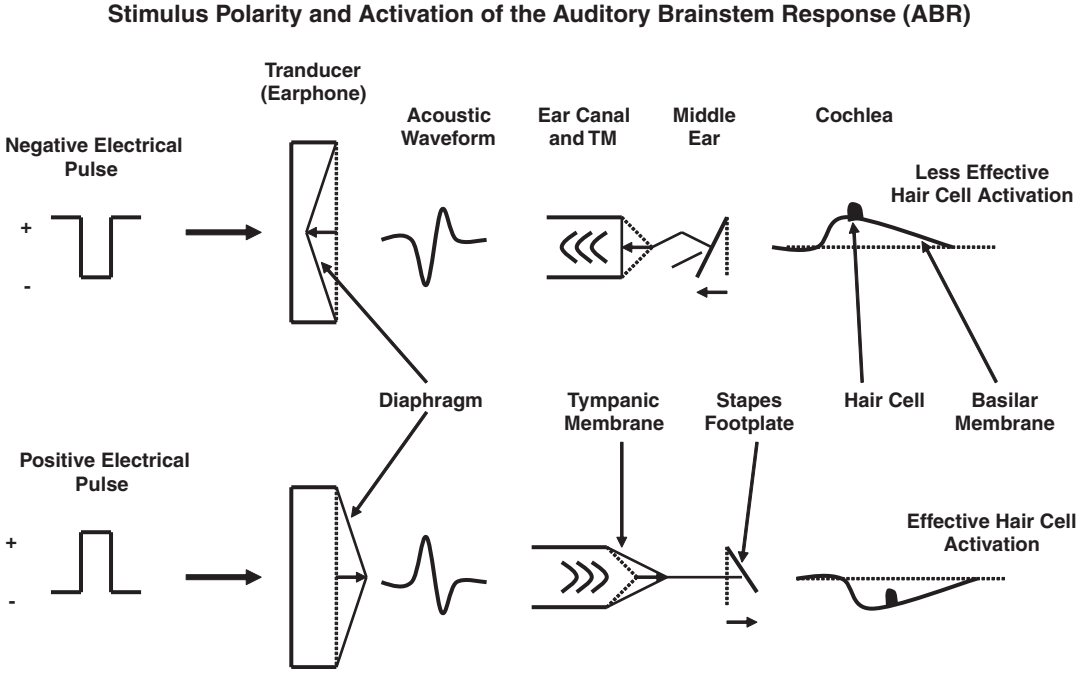

FIGURE 3.3. Schematic illustration of the sequence of events related to activation of the ear with by acoustic stimuli with rarefaction polarity.

is acoustic and the transducer is an earphone. Electrically elicited AERs, recorded most often in cochlear implant patients, are an exception to this rule (see Chapter 15). Transducers for AER measurement receive an electrical signal and produce a sound that is presented as an air-conduction stimulus. An air-conduction acoustic stimulus may also be presented with a loudspeaker. Even though loudspeakers are a common transducer type in behavioral audiologic assessment, they are rarely used in AER measurement. In some instances, AERs are elicited with bone-conduction (versus air-conduction) stimulation. An oscillator or vibrator is placed on the skull. The electrical signal with this type of transducer does not produce a sound; instead, mechanical oscillation is transmitted to the inner ear fluids, largely by vibration at the test frequency of the temporal bone (within which the inner ear is encased). The use of bone-conduction oscillators in eliciting AERs is discussed in a later subsection.

TDH-39 Earphone with MX41/AR Cushion

An array of transducers that are used in presenting stimuli in AER measurement is shown in Figure 3.4. Until the early 1990s, acoustic stimuli were presented via a Telephonics TDH-39 earphone mounted in an MX41/AR cushion. The apparent reasons for selection of the TDH-39 earphone in AER measurement were its availability, the security of knowing that it was routinely used in clinical audiometry, and the existence of pure-tone and speech audiometry standards for this earphone. However, there is really no rationale for continued reliance on the TDH-39 earphone and MX41/AR cushion as the transducer of choice in AER measurement. There are compelling arguments for abandoning the practice in favor of insert earphones. The TDH-39 is an electrodynamic earphone with low electrical impedance. At high intensity levels, the TDH-39 (and most transducers) produces an electromagnetic field that results in stimulus artifact. This is a clinical disadvantage. Electromagnetic shielding of the earphone and part of the cable has been recommended (Coats, Martin, & Kidder, 1979; Elberling & Salomon, 1973) to eliminate electromagnetic artifact, but commercially available shielded earphones are far more expensive than unshielded earphones. The use of piezoelectric or electrostatic earphones, instead of the electromagnetic type, is also an effective but probably equally expensive means of eliminating stimulus artifact in AER recording (Hughes & Fino, 1980). However, with piezoelectric earphones, a larger voltage is required because of the high impedance. This may limit the maximum intensity level output.

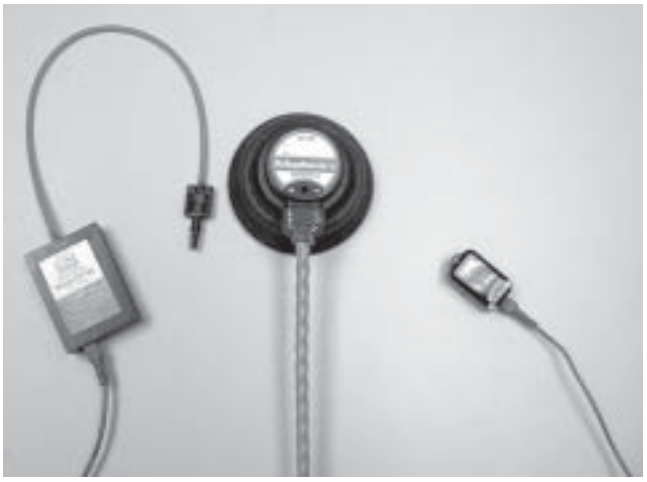

FIGURE 3.4. An array of transducers for presenting acoustic signals in the measurement of auditory evoked responses. From left to right the transducers are insert earphone, supra-aural earphone, and bone oscillator.

When mounted in the standard sponge rubber MX41/AR cushion (shown in Figure 3.4), the TDH-39 or TDH-49 is a supra-aural earphone. That is, the earphone rests on the ear and also makes contact with the head. This is distinct from a circumaural cushion, such as the Pederson type, which encompasses the ear and rests entirely on the head. Although TDH-39 or TDH-49 earphones with the MX41/AR cushion occlude the ear and enclose a relatively small volume of air under the cushion, there is often a gap or space below the ear in the region of the jaw. This gap permits leakage of, primarily, low frequencies (250 Hz and lower). Removal of the earphone from the cushion, which was reported in early reports of ABR measurement of newborn and young children, may dramatically alter the acoustic characteristics of the stimulus and also reduce ambient noise attenuation. This practice is certainly not advised.

The TDH-49 earphone is externally identical to the TDH-39 earphone and is mounted in the same type of sponge rubber cushion (MX41/AR). Of these two earphones, the TDH-49 is better suited for AER measurement, at least with high-frequency or broad-spectrum (e.g., click) stimuli. The frequency response for the TDH-39 earphone is illustrated in Figure 3.5. *It is important to keep in mind, however, that insert earphones are generally best suited for auditory evoked response assessment, especially with children.* Practical differences between the two supra-aural earphones in ABR measurements are enumerated next. These differences among earphones were based on analysis of acoustic spectra within a 6 cc coupler (a hard-walled cavity). The acoustic spectra are further transformed (modified) by the human external ear and ear canal (Pickles, 1988). When measured with a probe-tube microphone in the ear canal located close to the tympanic membrane, characteristics of the stimulus, including the spectrum, are not the same as in the coupler. The intensity level differences between these two types of measurements (coupler versus real ear) are greatest for frequencies below 500 Hz and, importantly for ABR stimulation, in the 2000 to 5000 Hz frequency region (Cox, 1986).

Placement of the earphone cushion on the ear is a factor in AER measurement. Audiometric hearing threshold

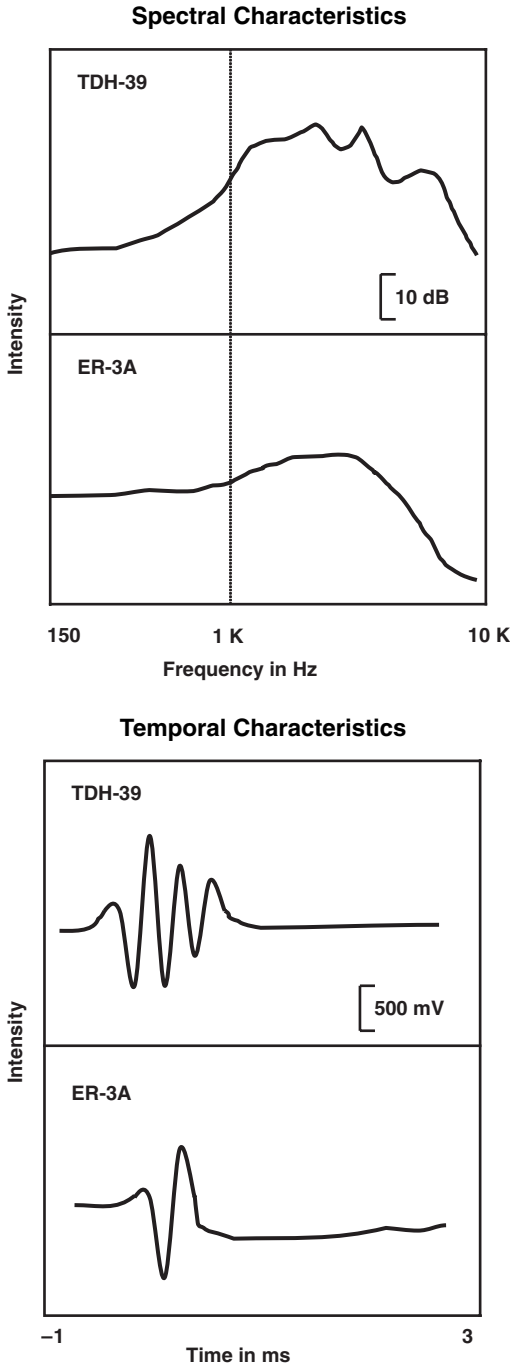

FIGURE 3.5. Temporal and spectral (frequency) responses for acoustic signals produced by TDH earphones versus Etymōtic ER-3A earphones.

standards and also AER intensity calibration on human ears assume that the earphone diaphragm is directly aligned with the external ear canal meatus and pressed against the pinna with no air leaks. In audiometric threshold assessment, care is taken to properly place the earphone and cushion on the external ear. The patient, who is sitting upright, is instructed not to move the headset. In AER measurement, test conditions may fall short of this ideal. Even cooperative adult patients are often in a reclining position. The headband, in its usual coronal position, may not remain in place. This can cause earphone slippage. Head movements may produce changes in earphone position that can easily go unnoticed by the tester. With infants, the problems of precise earphone placement are compounded. The external meatus is smaller, head movement may be greater, and the headband (designed for adult head sizes) is often too large even when adjusted as tightly as possible. If the infant prefers to sleep on her or his side (versus supine), even an approximate placement for the earphone on the ear on which the head is resting may be impossible. In combination, these test problems conspire to reduce accuracy in acoustic stimulation in AER measurement.

One solution to the problem of stabilizing earphones on infant ears during ABR assessment was a specially designed rigid headset developed by Zubick, Fried, Thebeau, Feudo, and Strome (1983). Conventional audiometric earphones were mounted in a support unit, which was firmly attached to an adjustable bar. The bar, in turn, was connected to an extension, which could be secured to a bassinet. This device reportedly kept the earphones in the desired place and restricted head and body motion, reducing test time by 50 percent in most cases. Clark, Dybala, and Moushegian (1998) reported another investigation of the effects of earphone design on the ABR as documented with real ear measurements. The ear coupler typically used with the ALGO2 automated ABR screening device, a foam donut-shaped cushion that fits over the external ear of the infant, was substituted by probe tip couplers that are fit to insert earphone tubes for infant ABR measurement. The 35 dB nHL stimulus intensity level, and the click spectrum, delivered by the ALGO2 with the conventional foam couplers was significantly changed by the probe tip coupler. Importantly, real ear measurements confirmed markedly higher SPL values in infant ear canals with the probe tip design, and the levels in the ear canal varied depending on the depth of the probe tip within the ear canal. As Clark, Dybala, and Moushegian (1998) note, "The neonatal AABR results show that coupler type and placement can also produce inaccurate screening evaluations and erroneous conclusions."

Insert Earphones

Over twenty years ago, Mead Killion and associates reported the development of a new type of transducer for air-conduction stimulation (Killion, 1984; Killion, Wilbur, & Gudmundsen, 1985). The Etymōtic Research (ER) transducer is enclosed within a small box (one for each ear), and the acoustic signal is directed through a tube to a foam plug that is inserted into the outer portion of the external ear canal (as shown in Figure 3.6). The plug is the same type (E.A.R.) that is often used for ear protection. The Etymōtic ER-3A transducer and foam plug insert assembly has desirable acoustic

characteristics, such as a wide and predictable frequency response. In fact, it was designed to mimic the acoustic characteristics of the standard audiometric earphone (TDH-39). Impedance of the insert earphones may be high (e.g., 300 ohms) or low (e.g., 10 or 50 ohms). *It is very important to use a set of insert earphones that is compatible with and selected by the manufacturer for your auditory evoked system.* When it is desirable to locate the evoked response instrumentation some distance from the patient, e.g., in the operating room, the stock cable for insert earphones with either impedance can be connected to an extension cable (e.g., 20 feet).

With insert earphones, there are a variety of options for coupling the insert transducer (see Figure 3.6) with the ear. For adults and older children, sound can be delivered to the ear via the acoustic tubing (see "C" in Figure 3.6) and a disposable polyurethane foam ear tip that is first compressed and then inserted into the external ear canal. Advantages of insert earphones in the measurement of auditory evoked responses are detailed below. The ear tips are available in two sizes (13 mm and 10 mm) (see "D" in Figure 3.6). For most male adult patients and some female adult patients, the larger size (13 mm and yellow) is a good fit. The smaller size (10 mm and beige) is appropriate for female adult patients and older children. *Take care in removing the ear tips from the silicone acoustic tubing to leave the little plastic connector ("nipple") within the tubing.* The connectors can easily be removed inadvertently with the ear tip and discarded. The next clinician to perform an auditory evoked response recording with insert earphones will, lacking the connector, be quite frustrated by the inability to attach an eartip to the acoustic tubing. The acoustic tubing for insert earphones should be inspected periodically for cracks and holes. If the integrity of the tubing is compromised, sound can escape and the intensity level of the stimulus is reduced. If biological calibration of the auditory evoked response stimuli (e.g., clicks or tone bursts) indicates reduced intensity levels, the clinician should immediately rule out a problem with the acoustic tubing. *Another warning—the length of the silicone acoustic tubing for insert earphones should never be modified (e.g., cut).* Shortening the length of the acoustic tubing will alter the time delay for presentation of the stimuli that evoke auditory evoked responses. When the user selects insert earphones as the transducer (and not supra-aural headphones or a bone oscillator), modern evoked response systems automatically adjust (decrease) latencies by a specific amount (e.g., 0.8 or 0.9 ms) to compensate for the time delay produced by the acoustic tubing. Cutting the acoustic tubing will reduce the actual time delay in the arrival of the stimulus to the ear and will produce a corresponding error in latency for auditory evoked responses.

Insert earphones can be used with infants (including neonates) and other younger children by coupling a special connector to the acoustic tubing (see "A" in Figure 3.6). The medial end of the connector (or adapter) is a narrow, black, cone-shaped plastic device that fits into the bore (center hole) of rubber probe tips (see "B" in Figure 3.6). With these connectors, available also from manufacturers of auditory evoked response equipment, it's possible to attach probe tips used typically for aural immittance measurements with tip sizes ranging from very small (a thin layer of rubber) to very large probe tips. Rubber probe tips used with insert earphones can be discarded (some are disposable) or cleaned for reuse with an appropriate hospital-approved disinfectant. Of course, despite their many clinical attributes, insert earphones are of no value in patients with aural atresia who lack an external auditory canal. Clinicians who perform auditory evoked response assessments in children should have, in addition to the insert earphones, a set of supra-aural (e.g., TDH) earphones that are compatible with the instrumentation for such cases.

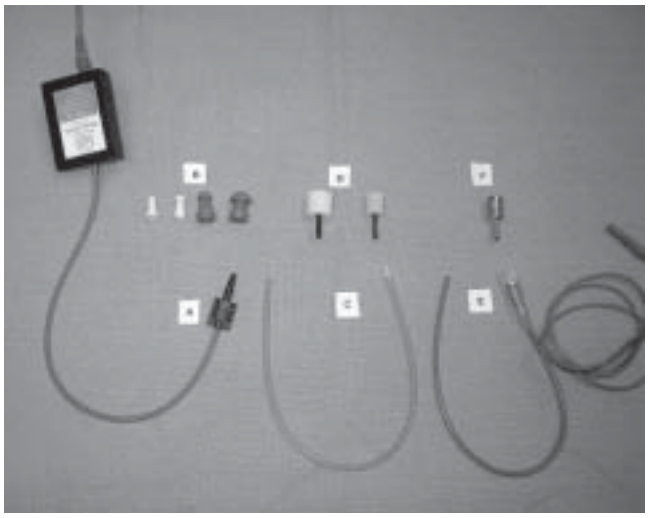

FIGURE 3.6. Options for coupling the acoustic tubing of insert earphones to the ear canal with pediatric and adult patients.

The Etymōtic ER-3A offers at least twelve potential clinical advantages over conventional audiometric earphones, as summarized in Table 3.3. Some of the advantages will now be highlighted. The problem of stimulus artifact extending into the region of early AER components, such as the ECochG AP component or the ABR wave I component, is essentially eliminated by the time delay introduced by the tubing. This feature of the ER-3A is illustrated in numerous waveforms throughout this book. The length of the Etymōtic ER-3A tubing (about 280 mm) produces an acoustic travel time from the transducer to the insert of about 0.9 ms. Recall that the speed of sound is 350 meters/second or 1100 feet/second. Electromagnetic energy generated by the ER-3A transducer can be removed from the recording electrode, which is located on the earlobe or the mastoid of the stimulated side. In fact, it is good clinical technique to extend the tubing and place the transducer as far from the ear

TABLE 3.3. A Dozen Clinical Advantages of Insert Earphones in Auditory Evoked Response Measurement

- Increased interaural attenuation of acoustic signal
- Increased ambient noise reduction (patient is essentially wearing sound-attenuating ear protection)
- Reduction of ear canal collapse (in infants)
- Increased patient comfort
- More precise placement in infants with small and soft ear tips, versus hand-held imprecise placement with supra-aural earphones
- Aural hygiene and infection control (insert cushions are disposed after single patient use)
- Insert earphones can be used as TIPtrode electrodes
- Insert cushion and tubing can be sterilized for intraoperative use
- Nonsterile portion of the earphone can be placed outside surgical field
- Flat frequency response (versus supra-aural earphones)
- Reduced transducer ringing with transient (click) signals
- Reduced stimulus artifact by separating the transducer box and the electrode (extend tube from ear and keep insert transducer box away from electrode wires)

(and electrode wires) as possible (see Chapter 7). In contrast, the TDH-39 earphone is essentially resting on the earlobe electrode. As a result, the use of TDH earphones can be associated with substantial stimulus artifact that encroaches on the wave I component of the ABR and precludes accurate identification and analysis. Stimulus artifact need not be a problem for the ER-3A.

Two precautions should be stated at this point. First, the travel time delay of the stimulus must be considered. Although the time delay is constant (0.9 ms), AER analysis time period for commercially available evoked systems is initiated at the time of the stimulus trigger, not when the stimulus reaches the ear. Therefore, absolute AER latency values are lengthened by 0.9 ms and need to be corrected by subtracting this time from the wave component latency. For example, an ABR wave V latency with ER-3A stimulus presentation of 6.50 ms would be corrected to 5.60 ms (6.50 minus 0.90 = 5.60 ms). Current AER systems adjust latencies for the tube delay when the insert earphone transducer option is selected. Interwave latency values and all amplitude calculations are not affected by the tubing time delay factor. The second precaution, naturally, is that if ER-3A tubing is cut or replaced with tubing of another length, this stimulus time delay will be altered. Also, it is important to recognize that the acoustic characteristics of the stimulus produced by the Etymōtic ER-3A were shaped taking into account the effect of tubing with these dimensions (length and diameter). Any change in the dimensions will modify the acoustic spectrum of the stimulus. The manufacturer strongly recommends using the tubing supplied with the transducer.

Another advantage of the ER-3A earphone is related to the temporal waveform of the click stimulus. As shown in Figure 3.5**,** the ER-3A earphone has limited acoustic ringing, in comparison to TDH earphones. That is, the extra deflections in the temporal waveform after the initial earphone response to the rectangular electric pulse, clearly evident for the TDH earphones, are not observed for the ER-3A "tube phone."

Also, insert earphones are quite effective in preventing the collapse of ear canals. The pressure of supra-aural earphones and cushions can cause the cartilaginous outer portion of the external auditory canal to collapse and occlude the opening. This problem tends to be more prevalent in infants and in the elderly. The problem of infant ear canal collapse with supra-aural earphones is, however, not inevitable. Galambos and Wilson (1994) systematically compared absolute thresholds for ABRs recorded from thirty-one ears of twenty-eight infants with an insert earphone and with a supra-aural earphone design. Estimated thresholds never differed by more than 10 dB, leading the authors to conclude that the supra-aural earphone "rarely if ever collapses the ear canal to cause an artificial conductive hearing loss." The effect of ear-canal collapse and occlusion is a worsening of air-conduction hearing thresholds for high frequencies. For behavioral hearing threshold levels, the decrease is on the order of 10 to 20 dB in the 1000 to 8000 Hz region. Bone-conduction hearing thresholds are, of course, not affected. Collapsing ear canals attenuate the stimulus intensity actually reaching the cochlea. For AERs that depend on higher frequencies of click stimuli (ECochG and ABR), latency values can be increased and response thresholds elevated by this reduced intensity. In newborn auditory screening at an intensity level of 30 to 40 dB nHL, an unrecognized collapsing ear canal can lead to an erroneous screening failure.

In addition, the insert cushion reduces concern about possible crossover of the stimulus from the test ear to the nontest ear. The interaural attenuation of the head, the "sound insulation" created between ears by the head, is approximately 40 to 50 dB HL. When an air-conduction stimulus presented to one ear via a conventional earphone exceeds the interaural attenuation, it is possible that some of the stimulus energy will reach the other (nontest) ear. Stimulus energy may seep around the earphone cushion and travel via air to the other ear, but the real problem with cross over is bone-conducted energy. That is, the earphone makes contact with the head and, at moderate-to-high intensity levels, stimulus-related vibration is transmitted from the earphone to the skull. Then, the vibrations reach the contralateral cochlea via bone conduction (bone-conducted sound also reaches the ipsilateral [test ear] cochlea). Because transfer of energy from the earphone to the cochlea via bone conduction occurs at high signal intensity levels, the conductive component of a hearing loss theoretically cannot exceed about 60 dB HL. The ER-3A foam insert makes contact with only the cartilaginous portion of the external ear canal, not the

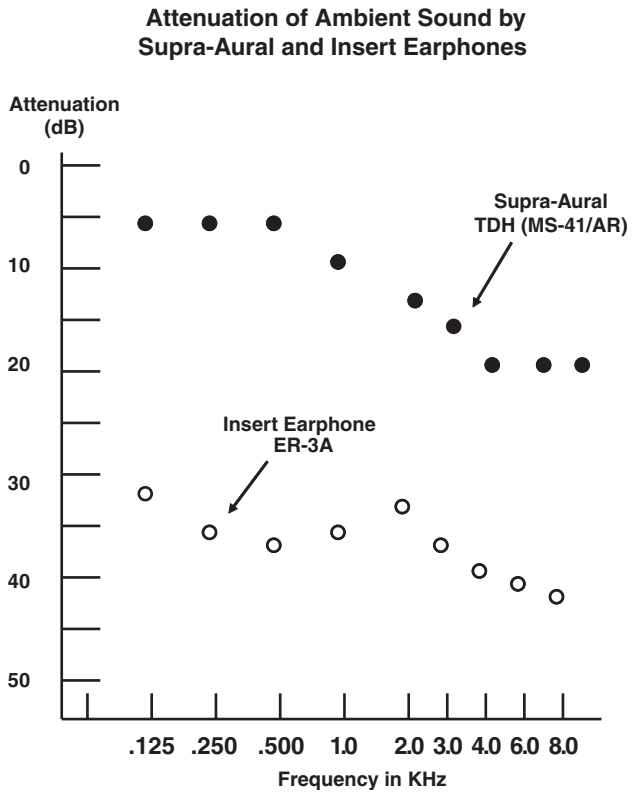

FIGURE 3.7. Sound attenuation levels for supra-aural earphones versus insert earphones as a function of signal frequency.

bony portion, and crossover may not occur until stimulus intensity reaches 70 dB or greater. That is, interaural attenuation is increased when the ER-3A insert earphone is used instead of the TDH earphones. The maximum increase in ER-3A interaural attenuation, relative to TDH earphones, is for frequencies of 100 Hz and below. Click-evoked ECochG and ABR measurements, however, are most dependent on higher frequencies. Reliance on the ER-3A earphones does not eliminate possible stimulus crossover or the need for masking in air-conduction AER measurement. This point is further discussed in the section on masking.

A related advantage results from the sound-attenuating properties of the ER-3A foam plug. As noted, this plug is the same type that is used to protect the ear from excessive environmental noise. It has been found to attenuate ambient noise in the AER test setting by approximately 30 dB (Figure 3.7). Also, the ER-3A stimulus-delivery arrangement ensures proper earphone placement, assuming that the probe cushion is securely fitted within the ear canal. A moderate amount of patient movement does not usually dislodge the insert. The slippage problem noted for the standard audiometric earphone/cushion is eliminated. A secure insert is particularly helpful for testing newborns. Not only is placement consistently precise, but also there are none of the difficulties associated with handholding the earphone or attempting to present a stimulus to the downward-facing ear of a patient sleeping on her or his side. A practical clinical advantage is comfort. The conventional audiometric headset is rather inflexible and rather uncomfortable during extended use. When the standard headset is resting on earclip electrodes, patients may actually complain of pain over time. Patients seem to prefer the spongy insert plugs. In the interest of aural hygiene, it is necessary to begin each test session with a new set of the insert earplugs. Indeed, infection control is a real-world benefit of using disposable insert ear cushions in a clinical setting.

Systematic study of ER-3A earphones was conducted following their introduction as a clinical transducer option. Beauchaine, Kaminski, and Gorga (1987) compared the performance of Etymōtic ER-3A insert earphones versus a circumaural earphone (Beyer DT48) in ABR measurement in ten normal-hearing adult subjects. Behavioral thresholds for a click stimulus were equivalent for the two earphone types (mean difference of 1.33 dB, with a standard deviation on the order of 5 dB). ABR thresholds were slightly elevated for the ER-3A versus the circumaural earphone (average of 10.63 versus 6.88 dB), but within the 5 dB intensity increment used in the study. As expected, ABR latency values increased with decreasing intensity for each earphone type, as did variability for latency. Wave V latency variability, however, appeared to be larger for the ER-3A. No explanation for this finding was offered. An absolute latency prolongation for wave V of 0.88 ms for the ER-3A (versus the circumaural) was consistent with the delay caused by the tubing (explained previously). Interpeak latencies (wave I–III, wave III–V, wave I–V) were comparable for the two earphones. Therefore, the authors state that only a simple latency correction to account for the tubing-related time delay is required to equate the ABR data for the two earphone types. Finally, the study was among the first to demonstrate the clinical feasibility of the ER-3A earphone with neonates.

Bone-Conduction Stimulation

A detailed discussion of theories on bone conduction of sound and principles and procedures for assessment of bone-conduction hearing is beyond the scope of this book. Information is available in numerous audiology texts. Briefly, the cochlea can be activated by sounds arriving via air or bone conduction. With the air-conduction route, sound (1) enters the external ear, (2) travels to the tympanic membrane through the external ear canal, (3) vibrates the tympanic membrane, which, in turn, (4) vibrates the ossicles and oval window, and (5) produces a traveling wave along the basilar membrane, which (6) activates the cochlea at the hair cells. The air-conduction route is an effective way of activating the cochlea because sound is amplified (energy is increased) by three factors: (1) the resonance properties of the ear canal, (2) the ratio of the area of the tympanic membrane versus the oval window, and (3) the lever action of the ossicular chain.

Bone-conduction hearing also results in activation of the cochlea, and, thereafter, hearing processes are presumably the same as for air-conduction stimulation. The mechanism of sound transmission to the cochlea via bone conduction is, however, not completely known. The work of von Békèsy (1960) and Tonndorf (1966), among others, suggests three probable bone conduction mechanisms that interact in some combination to activate the cochlea:

- Inertial bone conduction (in which the temporal bone is accelerated by a stimulus): As the temporal bone (including the bony cochlea) vibrates, the stapes footplate (the part of the ossicular chain nearest the cochlea) and cochlear fluids lag behind. Inertia of these two structures, in effect, produces both an in–out motion of the stapes footplate, similar to the air-conduction ossicular chain vibration, and a relative flow of cochlear fluid, both of which ultimately activate hair cells.
- Compressional bone conduction: Distortional vibrations of the temporal bone, when they arrive at the bony walls of the cochlea, produce traveling waves within the cochlea.
- Osseotympanic conduction: Vibrations in the temporal bone arriving at the walls of the bony portion of the external ear canal generate acoustic energy in the ear canal, which then eventually activates the cochlea via the aforementioned air-conduction route.

Although adequate bone-conduction stimulation can be presented anywhere on the head, including such unorthodox locations as the bony portion of the nose, the teeth, and the jaw, the two clinically most common vibrator placements are the mastoid bone (behind the lower part of the ear) and the frontal bone (forehead). Frontal placement produces more reliable threshold results, but mastoid placement is traditionally used, probably because it permits a higher effective intensity level to reach the cochlea. The expected decrease in the effective bone-conduction intensity level from mastoid to forehead placement for selected test frequencies are 15 dB at 500 Hz, 10 dB at 1000 Hz, 8.5 dB at 2000 Hz, and 6.5 dB at 4000 Hz. These values were derived from human studies with steady state (versus transient) pure-tone stimuli. For a brief-duration (2.5 ms) tone burst of 2000 Hz, Boezeman, Kapteyn, Visser, and Snel (1983) found a mastoid-to-forehead decrement of 7 dB.

A factor that can influence bone-conduction thresholds, as measured with behavioral audiometry and also with AERs, is the occlusion effect. When a normal-hearing ear is covered (e.g., with an earphone), bone-conduction threshold levels for occlusion effect are relatively greater for lower frequencies (approximately 20 dB at 500 Hz and 10 dB at 1000 Hz) and negligible for higher frequencies. The difficulties and dangers in generalizing these types of data to bone-conduction stimulation of AERs with transients are reviewed next.

One bone-conduction vibrator shown in Figure 3.4 is a Radioear B-71. Other commercially available bone vibrators (e.g., Radioear B-70) have a similar external design. The clinician was alerted above to the importance of using insert earphones and supra-aural earphones with impedance that matched the specifications for the evoked response system (e.g., low or high). The same concern applies to bone-conduction oscillators (bone vibrator transducers), as they are available in low impedance (e.g., 10 ohms) or high impedance (e.g., 300 ohms) versions. Numerous authors note that bone vibrator output declines in the high-frequency region that is important for click stimulation (Mauldin & Jerger, 1979; Schwartz & Berry, 1985; Weber, 1983b; Yang, Rupert, & Moushegian, 1987). Output levels from three commercially available bone vibrators were compared with those of two air-conduction earphones (TDH-49 and a hearing-aid transducer plus insert plug) by Schwartz, Larson, and DeChiccis (1985). The air-conduction transducers produced a relatively flat frequency response, while each of the bone-conduction vibrators had energy predominantly in the 2000 Hz region, with maximum output not exceeding 35 dB HL. Of the three bone vibrators, the B-70 permitted greatest output. The preceding information on bone vibrators may not accurately reflect their potential for AER measurement (Gorga & Thornton, 1989). The reduction of bone-vibrator output for higher frequencies, when expressed in units of force, may not necessarily correspond to a diminished effective intensity level in this audiometric region. Bone-vibrator output is indeed reduced above 2000 Hz, but then so are behavioral hearing threshold levels. Consequently, effective output of the bone vibrator is actually greater in the higher frequency region. Bone oscillator placement in infants and young children is somewhat more challenging, due to smaller head dimensions and the design limitations of the typical headbands, than with older children and adults. Techniques for placement of the bone oscillator in pediatric AER applications, particularly ABR, are reviewed in Chapter 6.

Other problems shared by commercially available series of bone vibrators are excessive distortion and intersubject variability. The distortion, which is more pronounced with higher intensities, reduces or may even eliminate frequency-specific AER stimulation (Harder, Arlinger, & Kylen, 1983). The static force of bone-vibrator placement is another, often overlooked, factor in the effectiveness of bone-conduction stimulation. A force of 500 gm is generally preferred in audiometric bone-conduction measurement. Force of bone-vibrator placement is highly variable in clinical measurement and has not yet been systematically investigated in AER recording. Variability is due to inconsistencies in placement site and the pressure with which the vibrator is held to the skull and differences in skull impedance (Arlinger & Kylen, 1977). A predictable reduction in effective stimulus level occurs for forehead versus mastoid vibrator placement. Because of variations in skull impedance, it must be reemphasized that descriptions of the acoustic spectrum and intensity characteristics of bone vibrators, based on analysis with artificial mastoids, are probably not representative of

the properties of the mechanical (vibration) stimulus actually activating the cochlea.

Furthermore, when interpreting bone-conduction ABR data, it is important to keep in mind that the actual characteristics of the stimulus reaching the cochlea for a given subject may be substantially altered by the transmission properties of the skull (Arlinger & Kylen, 1977). For example, there may be more acoustic radiation for some bone oscillators than for others. Acoustic radiation, which is air-conducted sound leakage from the bone vibrator, is undesirable because at higher test frequencies (e.g., 4000 Hz) a subject may actually hear the bone-conduction stimulus via air conduction at an intensity level better than his or her true bone-conduction threshold (Frank & Crandell, 1986).

Finally, as mentioned in the section on intensity, approximately 40 to 45 dB of effective intensity is lost in going from air to bone conduction. Therefore, if a bone vibrator is plugged into the earphone stimulus, jack of an evoked response system the actual output, even at a maximum attenuator dial or instrument intensity reading of 95 dB, will only be at most 45 to 50 dB nHL. Put another way, the intensity level (as indicated on the dial or the monitor screen) required for just detecting a bone-conduction click stimulus (0 dB nHL), at least in a young adult, is approximately 40 dB. Because the maximum equipment intensity reading is 95 dB, this leaves an effective range of only about 55 dB for bone-conduction stimulation. This intensity limitation applies as well to traditional bone-conduction pure-tone audiometry.

CONTRALATERAL MASKING IN AER MEASUREMENT

Masking, according to the ANSI (American National Standards Institute) standard on "Acoustical Terminology" (S1.1; ANSI, 1960), is "the amount by which the threshold of audibility of a sound is raised by the presence of another (masking) sound" (p. 46). In AER measurement, there are two broad clinical applications of masking. As already discussed earlier in this chapter, noise with specific frequency characteristics can be presented to the test ear, along with a stimulus to reduce or, one would hope, eliminate certain portions of the cochlea from contributing to the AER. Selective masking of certain frequency regions in the ipsilateral (stimulus) ear is one technique for enhancing the frequency specificity of a stimulus. Contralateral masking of the nontest ear, used more often clinically than ipsilateral masking in both conventional behavioral audiometry and AER measurement, is the focus of this discussion. Masking noise is presented to the nontest (nonstimulus) ear, in an attempt to ensure that the nontest ear does not contribute to the response. Before considering the use of masking in AER measurement, a few remarks about terminology are in order. Masking noise is generally described both by its effective intensity level in dB and by its spectrum (frequency content). Broadband noise (BBN) is also referred to as "white noise," as an analogy to white light, which includes a wide range of wavelengths (and therefore colors). It is important to keep in mind that the effective frequency range of any broadband stimulus presented to an ear is, in fact, determined by the frequency response of the transducer, usually an earphone. The frequency response of most audiometric earphones begins to fall off for frequencies above 5000 to 6000 Hz and, therefore, so does the masking noise energy above this limit.

The spectrum of masking noise is often determined by filtering out energy in the undesired frequency region and by passing through energy at the frequencies of interest. Thus, a high-pass noise with a cutoff of 1000 Hz is derived from a broadband or white noise that is sent to a filter, which removes frequencies below 1000 Hz and which passes the frequencies above 1000 Hz. The cutoff is usually defined as the frequency at which the amplitude of the masker (or filtered noise) has decreased by a certain amount, such as by 3 dB (the 3 dB down point). A band-pass filter will remove both frequencies below a low-end cutoff (by means of a high-pass filter) and frequencies above a high-end cutoff (by means of a low-pass filter), resulting in a band of frequencies that pass through within these two cutoff points (e.g., 500 to 2000 Hz). Terminology used to describe filters may at first appear confusing. For example, a low-pass filter actually filters or eliminates high-frequency information, and the low-pass filter setting is actually the upper end of the frequency range that is passed. An understanding of such terminology is important in AER measurement, however, as it is also used in discussing the filters employed in recording and averaging evoked responses. Another masking principle in the measurement of auditory evoked responses should be noted at this juncture. The spectrum of the masking noise should be consistent with the signal used to evoke the response. For example, when an ABR is elicited with a broad-spectrum signal (e.g., a click), a broadband masking noise (e.g., white noise) is appropriate. On the other hand, with a tone burst signal (e.g., 1000 Hz), a narrowband masking noise (e.g., 500 to 1500 Hz) is most effective.

At least seven clinical questions are relevant in a discussion of masking and AER measurement:

1. Is masking ever necessary?
2. If so, what stimulus conditions suggest it?
3. How should masking be presented?
4. What kind of masking is best?
5. How much masking is enough?
6. Are there central auditory nervous system effects of masking that might influence AERs?
7. Are there measurement conditions for which masking is counterproductive?

These general issues are addressed as completely as possible. Next, findings from the relatively few published

studies of masking and specific types of AERs are summarized.

Is Masking Always Necessary in the Measurement of AERs?

Perhaps the more appropriate question would be "Is masking ever needed in AER measurement?" Depending on the type of transducer used in the measurement of AERs, the intensity level at which air-conduction pure-tone signals first cross over from the test ear to the nontest ear may be as low as 40 dB. Clearly, interaural attenuation occurs at lower (fainter) intensity levels for supra-aural earphones (as low as 40 dB) than for insert earphones (usually greater than 60 dB). Interaural attenuation between subjects also varies as a function of test frequency. Interaural attenuation is relatively less for lower frequency pure-tone stimuli, at least with the long durations used in behavioral audiometry. In general, interaural attenuation for click stimuli is in line with that for high frequency pure-tone signals—that is, approximately 65 dB for the average adult subject (Chiappa, Gladstone, & Young, 1979).

The crossover of click signals, as assessed behaviorally, would appear to present the same clinical problem for AER measurement as pure-tone audiometry. There are, however, three methodologic differences between the two procedures that are relevant to decisions about masking. First, AERs are very time dependent, whereas stimulus and response timing is a minimal concern in behavioral audiometry. In behavioral audiometry, only the intensity level of the sound crossing over to the nontest ear is critical. In contrast, both the intensity level of the sound and the time it takes to cross over are factors in AER measurement, particularly for the shorter latency responses (ECochG and ABR).

Second, the intensity level of the click stimulus reaching the nontest ear is, of course, decreased by the amount of interaural attenuation for the subject. It might be instructive to consider a worst-case scenario for the problem of signal crossover for the ABR. Assuming there is total deafness in the test ear (a "dead ear") and there is normal hearing sensitivity, and a completely normal ABR, in the nontest ear, a very high intensity level click, such as 95 dB nHL, might be used. If so, one might expect that the click would stimulate the nontest ear at an intensity level of about 30 dB HL, i.e., 95 dB nHL minus 65 dB of interaural attenuation. An ABR would be elicited from the "good ear" with latency values corresponding to this intensity level (30 dB), plus the latency delay due to transit time from one ear to the other.

A third factor distinguishing AER measurement has to do with recording electrophysiologic versus behavioral responses in general. Distinct differences in behavioral versus ABR thresholds as a function of rate and duration have already been described in this chapter. Such differences are especially relevant to the discussion of masking. An ABR, for example, elicited by the air-conduction stimulus reaching the nontest ear will not have a wave I component when recorded with an electrode located on the test ("dead") ear side. An electrode located on the nontest ear, in dual channel recording, may show a wave I component, although at an effective intensity level of 30 dB, it would be unlikely. This concept is reviewed for ABR in more detail in Chapter 7. The main point is quite straightforward. A normal ABR, that is, a well-formed ABR with normal latencies for all wave components for a given high intensity level, cannot be recorded from a stimulus crossing over to the nontest ear. At best, in adults at least, the ABR resulting from crossover of the acoustic signal will be markedly delayed in latency and will lack a wave I component.

Masking is sometimes necessary in clinical AER measurement because responses reflecting auditory pathology, such as a waveform with only a markedly delayed wave V, may also fit the description of a response elicited by a signal that has crossed over from the test ear to the nontest ear. This important clinical principle was not always appreciated in early studies. Finitzo-Hieber, Hecox, and Kone (1979), for example, presented a patient with total unilateral impairment, who showed no ABR for a 90 dB click stimulus presented to the involved ear. According to the authors, "the results suggest that contralateral masking may not be needed for air-conducted brain stem evoked responses to click stimuli" (p. 1156) and added that "the ability to omit contralateral masking from the evaluation procedure simplifies and shortens the test procedure considerably" (Finizo-Hieber, Hecox, & Kone, 1979, p. 1157). Galambos and Hecox (1978) expressed a similar opinion.

Accumulated experience clearly indicates that when click stimuli are presented to a profoundly impaired ear at intensity levels exceeding 75 to 80 dB nHL, an ABR can be elicited from the contralateral (nontest) ear (Hatanaka, Yasuhara, Hori, & Kobayashi, 1990; Reid, Birchall, & Moffat, 1984; Rosenhamer, Lindstrom, & Lundborg, 1978; Smyth, 1985). Smyth (1985) convincingly demonstrated that in patients with unilateral hearing loss, the nontest ear must be adequately masked for valid interpretation of ABR findings. ABRs for click stimuli (TDH-49 earphone) were recorded from a normal-hearing control subject and four patients with unilateral hearing impairment: one with conductive impairment; one with a flat, severe sensorineural impairment with recruitment; one with a moderate-to-severe sloping sensorineural impairment without recruitment; and one with profound sensorineural impairment.

Smyth (1985) concluded that an auditory response due to signal crossover was a serious clinical concern in ABR measurement, although ABR latencies due to the crossover of stimulation to the nontest ear were almost always abnormal. Without the inclusion of masking, the degree of hearing impairment in the poorer ear could be underestimated, and the type of loss could be misinterpreted. For example, a retrocochlear lesion could be erroneously inferred from a grossly delayed response due to a profound

cochlear deficit. Obtaining an ABR from the poorer ear for a single high-intensity stimulus level, referred to by Smyth (1985) as "single-shot data acquisition" (p. 29) is particularly suspect and essentially invalid. Smyth (1985) gave a "resounding yes" to the question of whether masking should be used. The answers to when and how masking should be employed clinically, she said, depend on characteristics of the evoked response system, stimulus conditions, and, importantly, the patient's audiometric configuration. This final point is reiterated often in this text. Whenever the patient's age and level of cooperation permit, pure-tone audiometry should precede AER assessment. Some authors go so far as to recommend use of contralateral ear masking routinely in every ABR measurement, to prevent any possibility of crossover (Chiappa, Gladstone, & Young, 1979; Hatanaka, Yasuhara, Hori, & Kobayashi, 1990; Levine, 1981). Masking is not always required in ABR measurement, however. A more clinically appealing approach is to mask the nontest ear whenever cross over of the signal from the test ear to the nontest ear is likely to occur. Clinical indications for masking are summarized next and are reviewed more thoroughly in Chapter 7.

If Masking Is Sometimes Needed, What Measurement Conditions Suggest the Need for It?

Contralateral masking of the nontest is indicated in AER measurement for any patient with a unilateral auditory impairment when an air-conduction stimulus is presented to the poor ear (at an intensity level exceeding 70 dB nHL) and the response has abnormal latency values and no distinct wave I component. These criteria are rather specific and are not met by the majority of patients undergoing AER assessment. For this reason, masking is not routinely required. Contralateral masking is not needed if (1) AERs are unequivocally normal bilaterally, regardless of the stimulus intensity; (2) there is no detectable response unilaterally or bilaterally; or (3) there is a clear and reliable wave I component for stimulation of the poorer ear. Otherwise, masking is generally indicated to rule out a contribution from the nontest ear to the auditory evoked response.

One must also consider the possibility that even a completely normal-appearing AER for very high stimulus intensities may actually contain components generated by the nontest ear, components due to crossover of the stimulus. That is, an ABR with markedly delayed wave V can be recorded from a normal nontest ear when a high-intensity stimulus is presented to a contralateral "dead ear." Indeed, Reid, Birchall, and Moffat (1984) found that with a click stimulus at 90 dB and no contralateral masking, there was a larger amplitude wave VI component than with 50 dB of contralateral masking. At lower stimulus intensity levels, the masking produced no change in wave VI amplitude. These authors speculate that at high unmasked stimulus intensity levels, the wave V due to crossover of the signal sums with wave VI in the ipsilateral (stimulus) ear, thus enhancing wave VI amplitude.

How Should Masking Be Presented?

The three main ways that masking can be presented are with conventional air-conduction earphones, with newer insert transducers, and with bone conduction. For each of these presentation modes, the spectrum of the noise used as a masker depends, in part, on the frequency response of the transducer. The crossover to the nontest ear of energy for moderate- to high-intensity stimuli associated with the conventional supra-aural earphone is the reason why masking is needed for air-conduction assessment. Yet, this problem may apply as well to the masking noise. That is, if a moderate- to high-intensity masking noise is presented with these earphones to the nontest ear, there is a chance that it will cross over and inadvertently mask the test ear. This is referred to as the "masking dilemma." It is a function of masking intensity level and the substantial physical contact or coupling between the supra-aural cushion and the skull.

One clinical exception to this generalization was cited earlier. Yang et al. (1987) found higher interaural attenuation (lower likelihood of crossover) for newborns whose cranial sutures remain flexible and open. Interaural attenuation may be considerably higher for insert transducers than for supra-aural earphones, especially for lower frequencies. Bone conduction masking, as in the SAL procedure (Jerger & Tillman, 1960), has some distinct clinical advantages, but it has rarely been adapted to AER measurement (Hicks, 1980; Webb & Greenberg, 1984). The SAL technique does show promise for estimation of bone conduction hearing with the sinusoidal signals used to elicit the auditory steady state response (ASSR), as detailed in Chapter 8.

What Kind of Masking Noise Is Best?

For AERs elicited with click stimuli, a broadband masking noise presented to the nontest ear via air conduction is best. The click has a wide spectrum. Presumably, this same wide range of frequencies crosses over to the nontest ear, although there is little published evidence in support of this presumption (von Békèsy, 1960). The spectrum of the masking noise should at least equal or exceed the click spectrum. The preference for broadband noise for click-stimulated AERs contrasts with the routine and effective use of narrow bands of contralateral noise centered at pure-tone test frequencies in audiometry. Although narrowband noise maskers might conceivably be of value for AERs elicited by brief tone-pip stimuli, close analysis of the spectra of the stimuli would be needed first. As noted earlier, short-duration tonal stimuli may have considerable side bands and spectral splatter, which could contribute to the response, and which should be masked. Other types of noise applied sometimes in hearing science probably have no place in AER assessment. Finally, to ensure adequate masking, it is important that the

transducer employed to deliver the noise has a frequency response equal to that used to deliver the click stimulus.

How Much Masking Noise Is Appropriate?

It is difficult, if not impossible, to provide an answer to this question, especially an answer that applies to all possible stimuli, patient conditions, and test settings. There are different approaches for determining appropriate masking in behavioral audiologic assessment. For AERs, masking noise presented to the nontest ear at 50 dB nHL is adequate for even the highest AER click stimulus intensity level (e.g., 95 dB nHL). With an interaural intensity level of 65 dB for the click, the effective intensity level of the crossed-over stimulus in the nontest ear is about 35 dB nHL. This intensity level will invariably be sufficiently masked by 50 dB nHL, even in an ear with normal hearing sensitivity.

The rationale for selecting a routine noise level of about 50 dB is provided by evidence from an eloquent set of studies on noise effects on the ABR conducted by Burkard, Hecox, and colleagues (Burkard & Hecox, 1983; Burkard, Shi, & Hecox, 1990a,b; Hecox, Patterson, & Birman, 1989). The relationship between an ipsilateral masker level and ABRs for different click intensities—that is, the overall effect of broadband noise on ABR—is increased latency and decreased amplitude for wave V. Assuming that the crossed-over click stimulus intensity in the nontest ear is, at most, 40 dB nHL in ABR testing (95 dB HL intensity level –55 dB interaural attenuation), the crossover response will be completely masked by 40 dB. An added 10 dB masker intensity is suggested for an extra safety margin. However, more masking is not necessarily better. Masking noise levels greater than 50 dB nHL, in unilateral impairment, should be used very cautiously because there is the possibility that the masking noise will cross over to mask the test ear.

Are There Effects of Masking on the Central Nervous System?

Central masking in conventional audiometry occurs when the hearing threshold level in one ear increases with the presentation of a masking sound, even of low intensity, to the contralateral ear. There is no direct interference between the two sounds—that is, the masker and the stimulus are both well within the limits of interaural attenuation (both less than 40 to 50 dB HL). Animal studies indicate that central masking is mediated in the caudal brainstem auditory centers and pathways. Therefore, it is reasonable to question whether a similar phenomenon affects AERs recorded in the presence of contralateral masking, that is, whether the masking noise is activating brainstem or even cerebral neurons in the same general anatomic regions in which the AER generators are located. Perhaps these neurons, if responding to noise, will be less likely to give rise to AERs.

There is no definite central masking effect in ABR measurement (Boezeman et al., 1983; Chiappa, Gladstone, & Young, 1979; Prasher & Gibson, 1980a). Contralateral masking of the nontest ear, at low-to-moderate intensity levels (less than 70 dB HL), does not produce consistent alterations in ABR latency or amplitude. There is evidence that high-intensity contralateral noise crossing over to the test ear, or ipsilateral masking noise at a lower intensity, increases wave V latency and decreases wave V amplitude, but it has a less pronounced influence on wave I (Burkard & Hecox, 1983; Kramer & Teas, 1982; Lasky & Rupert, 1982). Rosenhamer and Holmkvist (1983) observed these contralateral effects and attributed them to central masking.

For Which Measurement Conditions Is Masking Contraindicated (Counterproductive)?

Routine masking for every patient undergoing AER assessment is not necessary and is probably not a wise test policy for three reasons:

- The masker becomes one more stimulus parameter that may be improperly set during AER assessment. An inappropriately high masker intensity level (greater than 70 dB nHL) presented to the ear contralateral to the stimulus ear may cross over and alter the AER in the test ear (Boezeman et al., 1983), perhaps leading to a false positive interpretive error.
- Another concern is that the masker will be presented to the same ear as the stimulus. Inadvertent ipsilateral masking can lead to a false positive AER outcome. For example, an ipsilateral broadband noise will usually artificially elevate AER threshold levels and may create nonpathologic ABR abnormalities. Also the ipsilateral masker may have little affect on ABR wave I but can produce an increase in wave V latency and a decrease in wave V amplitude. The resultant prolongation in the wave I to wave V latency interval and decrease in the V/I amplitude ratio are typical ABR signs of brainstem abnormality (Burkard & Hecox, 1983; Burkard & Voigt, 1989; Gott & Hughes, 1989).
- At high masking levels, the AER may be obliterated. For some evoked response systems, the masker is not automatically directed to the nontest (nonstimulus) transducer. If a masker is used, it is imperative that the masker is presented the opposite transducer when test ears are alternated. By avoiding the use of unnecessary masking this problem, too, is avoided.

ACQUISITION PARAMETERS

Analysis Time

In AER measurement, the analysis time should be long enough to encompass the response of interest under all test conditions. For the ABR evoked by click and high-frequency tone burst stimuli, a 15 ms analysis time (versus 10 ms) is

recommended because there are many circumstances that will delay wave V, and the subsequent negative voltage trough that aids in wave V identification, up to or beyond 8 to 10 ms. Factors contributing to such a delay would include immature CNS function in children, neuropathology, low stimulus intensity, low-frequency tone burst stimulus, and peripheral hearing impairment. A 20 ms analysis time is required when an ABR is elicited with lower frequency tone burst stimuli (e.g., 1000 Hz or 500 Hz). With any ABR test protocol, a prestimulus baseline (for example, 10% of the entire analysis period) is useful to assess the amount of nonresponse noise in the waveform noise. The prestimulus averaging period can be selected from the collection parameters or configuration page when an ABR test protocol is first developed. For the ABR, a prestimulus baseline period of 1 or 2 ms (actually –1 or –2 ms) is appropriate. The prestimulus period is apparent in most of the ABR waveforms displayed in this book as a line occurring before the stimulus (in the negative time region).

A short analysis period for ECochG is useful to eliminate ABR components from the waveform (e.g., wave III and wave V) and to enhance resolution and detection of the components of interest, such as the summating potential (SP) and action potential (AP). For cortical AER measurement, appropriate analysis times range from 100 ms for the AMLR to as long as 700 ms (100 ms prestimulus and 600 ms poststimulus) for the later responses (e.g., ALR and P300).

Electrodes

ELECTRODE SITES. | A collection of general-purpose commercially available electrodes is shown in Figure 3.8. Many other electrode types available commercially can be found in catalogs of supplies distributed by various manufacturers of auditory evoked response equipment. Electrode types are discussed in the next section. Appropriate electrode sites can make the difference between recording a well-formed response and not observing a response at all. Electrodes used for ECochG measurement are discussed further in Chapter 4, and in Chapter 7 for ABR. In AER measurement, and clinical neurophysiology in general, electrode sites are usually defined according to the International 10–20 system (Jasper, 1958). Electrodes used typically in AER measurement are labeled according to this system in Figure 3.9. There is a simple logic to the labels in the system. For example, electrodes containing the letter "z" are on the midline (anterior-to-posterior center of the head). The first letter of the label refers to the region of the brain over which the electrode is located, e.g., F = frontal, T = temporal, O = occipital, and P = parietal. The "C" electrodes are along the coronal line (corona = crown) from the vertex (middle top of the head) down each side to the ear canal. Cortical evoked responses are often recorded simultaneously with many electrodes located over the scalp.

There are several general principles relating electrode site and AER components. First, the closer the electrode is to

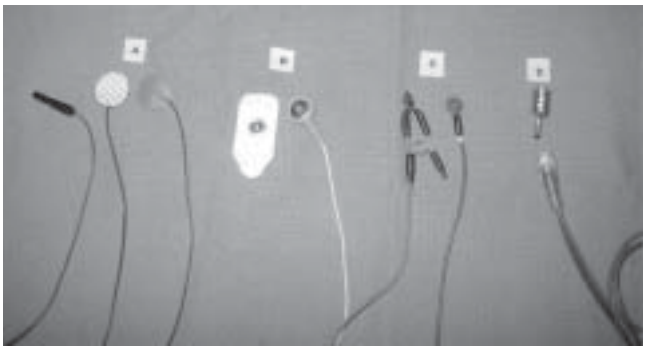

FIGURE 3.8. Electrodes commonly used for auditory evoked response measurement, including A. disposable electrode and cable, B. disposable electrode with snap-on cable, C. reusable metal disc electrode and ear clip electrode, and D. TIPtrode.

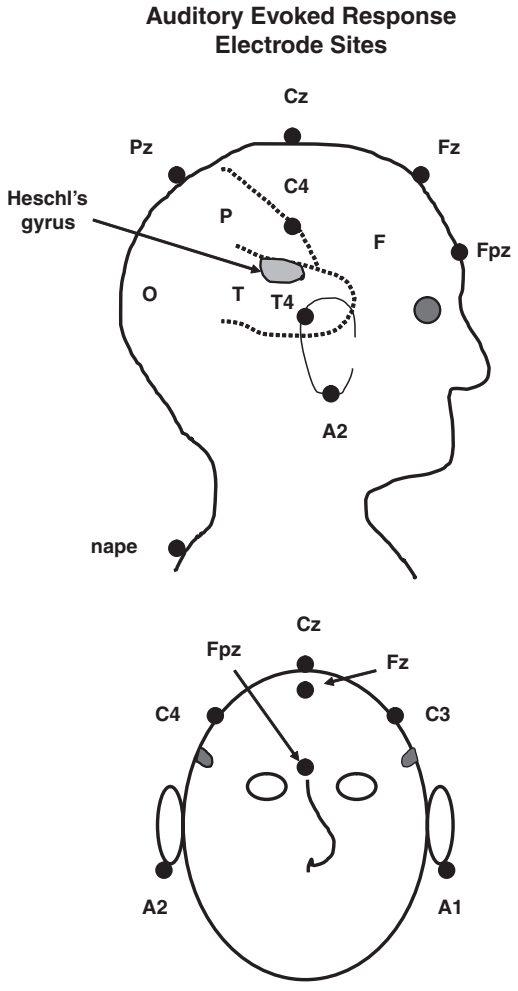

FIGURE 3.9. Electrodes locations labeled according to the International 10–20 system (Jasper, 1958) commonly used for auditory evoked response measurement.

the anatomic generator, the larger the response. For example, the ECochG AP component recorded from the promontory (lateral wall of the cochlea) may be 20 times larger than the AP recorded from the earlobe or mastoid. Second, in recording far-field responses from sites equidistant from the generator, such as the ABR, the exact location of the noninverting electrode is not crucial. The response is essentially comparable when recorded anywhere along the midline from vertex (Cz) to forehead (Fz). For ABR recordings, inverting electrodes located on the earlobe are preferable to mastoid sites, because wave I tends to be larger (up to 30%) and the electrode picks up less electromagnetic artifact from bone vibrators with the typical mastoid placement than with electrodes located on the postauricular region. It is possible that wave V amplitude may be slightly reduced with earlobe placement of the inverting electrode. Either of these sites (mastoid or earlobe) is, however, active with reference to electrical activity arising from the auditory system (especially cochlea, eighth nerve, and lower brainstem) and is not properly termed a "reference" or "indifferent" electrode. If interactions among noninverting and earlobe electrodes are suspected, on the basis of waveform morphology and/or difficulty identifying waves beyond I, then a noncephalic electrode site (e.g., nape of the neck) is indicated. The nape of the neck can be identified as the bump in center of the upper back where the neck joins the shoulders. Third, for neurodiagnostic applications, the AMLR should be recorded with electrodes located over each temporal-parietal region (C4 over the right hemisphere and C5 over the left hemisphere). The traditional midline noninverting electrode site for AMLR (Cz or Fz) appears to reflect activity from each auditory cortical region (right and left) or the more prominent hemisphere, in the case of unilateral cortical dysfunction.

Electrode Types and Application

Electrode application is a technical factor that is extremely important for successful evoked response measurement. The overall objectives are (1) consistent placement among subjects, (2) anatomically accurate placement, (3) low inter-electrode impedance (less than 5000 ohms), (4) balanced inter-electrode impedance (difference between electrodes of less than 2000 ohms), (5) secure and consistent attachment throughout the test session, and (6) minimal discomfort and no risk to the subject. After acquiring experience in AER recording, each clinician will develop his or her own preferences for electrodes, supplies, and technique. The following discussion, naturally, reflects the author's clinical experiences and is not presented as the "right" or only way to apply electrodes.

TECHNIQUES FOR APPLYING SURFACE ELECTRODES. | There are two main techniques for metal disc or disposable electrode application. With one technique, the connection between the electrode and skin is enhanced by a conducting gel or paste, and electrodes secured with tape or self-adhesive disposable electrodes are used. Included in the discussion of this technique are remarks about ear canal and tympanic membrane electrode placement. The other technique depends on collodion to secure the electrode and conduct neuroelectric activity. Since collodion is used less frequently by audiologists and by auditory neurophysiologists, the discussion of this electrode application approach is brief.

ELECTRODE APPLICATION. | A typical sample of supplies required for electrode application is shown in Figure 3.10. The electrode site is first prepared by scrubbing vigorously with one of several brands and variations of abrasive liquid substance designed for the purpose (e.g., NUprep^{R} as shown by "A" in Figure 3.10). The mild abrasion removes the natural oils of skin and superficial layers of skin, thus improving inter-electrode impedance. Alcohol pads serve the function of removing natural oils, as well as makeup and other cosmetic substances, from the skin, but regular use of alcohol by clinicians in electrode application, without the protection of rubber gloves, tends to leave the skin on fingers dry and even cracked. In addition, neonatologists have questioned the safety of preparing with alcohol the skin of newborn infants as there is a risk, albeit slight, that the alcohol will be absorbed and diffused into the bloodstream. Dry skin preparation pads are also an option prior to electrode application. However, the abrasive surface is typically not sterile, prompting concerns about the possible introduction of infection to abraded skin, particularly if scratches or abrasions compromise the integrity of the skin.

FIGURE 3.10. Supplies required for the application of electrodes used for clinical auditory evoked response measurement.

Before scrubbing an alert child or adult patient, it is good clinical manner to first describe briefly what is about to be done and to indicate that the scrubbing might be slightly uncomfortable. Of course, the same general explanation should be offered to the parent or caregiver of an infant before electrode application begins. In fact, it typically relieves the patient to learn that this is the "worst" part of the entire test. In routine clinical AER measurement, a small portion of mildly abrasive liquid is poured on a clean (not sterile) 2" × 2" or 4" × 4" gauze square (see "C" in Figure 3.10) and, with the index finger behind this part of the gauze, the electrode site is briskly rubbed (Figure 3.11). A cotton swab, (see "D" in Figure 3.10 and "A" in Figure 3.11) or an abrasive pad specially designed for electrode application, may also be used as an applicator. With a scalp site, the hair is first parted with the other hand. The earlobe site is prepared for electrode placement by grasping the earlobe between thumb and index finger with the gauze saturated with abrasive liquid, and then pulling downward briskly (see "D" in Figure 3.11). In preparing electrode sites around the eyes, it is important to keep the abrasive liquid from dripping into the eye. Excessive amounts of the liquid are wiped away with a clean portion of the gauze. Based on the observation of hundreds of students and neophyte auditory electrophysiologists applying electrodes prior to auditory evoked response measurement, the author concludes that timidity is a common technical flaw. For children and adults alike, test time will be saved and frustration with high interelectrode impedance avoided by initially scrubbing the skin vigorously with ample liquid abrasive substance. Adults and older children having been duly alerted in advance to the clinician's intentions will invariably tolerate this approach without protesting, whereas infants and younger children are likely to squirm and cry no matter how gentle the scrubbing.

There are two relatively minor issues that should be noted regarding electrode site preparation. One question is whether each site should be prepared and the appropriate electrode affixed before moving on to the next site, or whether all sites should first be scrubbed and then the electrodes applied. One could probably find experienced clinicians who would endorse both approaches. My approach is to prepare (scrub) the relatively "easy" standard AER electrode sites in rapid sequence (i.e., Fz, Fpz, earlobes, and, as indicated, a noncephalic location). "Easy" in this instance refers to sites with flat surfaces and little or no hair. Then, each electrode is dabbed with paste, applied, and taped following the same sequence. For ABR recordings, electrode application at four sites, i.e., Fz (high forehead in the middle), A1, A2, and Fpz (middle of the low forehead) is relatively simple and straightforward. Electrodes on the forehead are secured after placement with

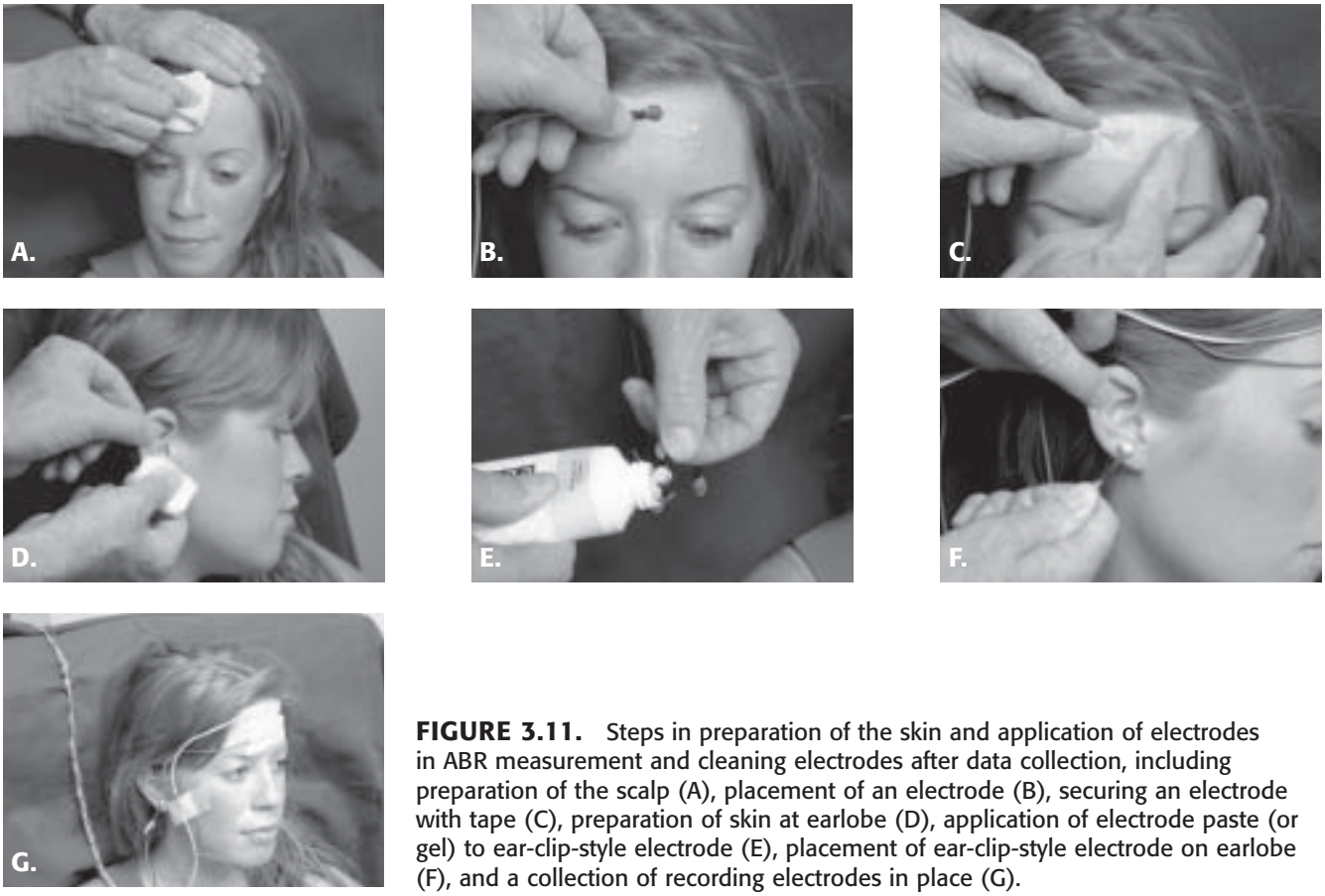

FIGURE 3.11. Steps in preparation of the skin and application of electrodes in ABR measurement and cleaning electrodes after data collection, including preparation of the scalp (A), placement of an electrode (B), securing an electrode with tape (C), preparation of skin at earlobe (D), application of electrode paste (or gel) to ear-clip-style electrode (E), placement of ear-clip-style electrode on earlobe (F), and a collection of recording electrodes in place (G).

short segments (1.5 to 2 inches) of tape (e.g., surgical tape or other medical-grade tape). Most clinicians experienced with auditory evoked response measurement have a preference for a specific type and material for the tape used to secure electrodes. Of course, tape is not necessary for the ear (inverting) electrodes with the earclip electrode design, and tape isn't required typically for any of the disposable electrodes used in ABR recording (as described below).

For electrode sites on hairy heads (e.g., hemispheric electrode sites for AMLR, or the Cz and Pz electrode sites for the ALR and P300 response), my approach is to prepare the scalp for one site, verify the location by keeping a finger in place, and then immediately apply the electrode with paste (*not* gel). Placing a cotton ball over the electrode that has just been applied to the skin with paste and pressing firmly for about 15 seconds will help to form a better and more durable connection. Then, one can move on to the next electrode site. Most electrode paste (as opposed to gel) actually adheres the electrode to the skin, although when possible tape should be used. Placing a second piece of tape on the electrode wire (lead) several inches from the electrode forms a "strain release" that helps to prevent electrode slippage (see "G" in Figure 3.11). This technique for electrode placement has several clinical advantages. It poses no risk to the patient and is relatively quick. Electrodes can be removed easily and the sites can be cleaned of paste or gel with an alcohol swab, diaper wipe, facecloth soaked in warm water, or any other suitable material.

Although there is little or no risk to the patient associated with ABR measurement, there is a remote possibility that the substances used to prepare electrode locations on the skin or to adhere electrodes to the skin will produce an allergic or other dermatologic reaction. Substances used for electrode preparation and placement (e.g., abrasive liquids, gel, cream, or paste) should be selected with regard to the manufacturer's recommendations for use with patients. For example, some brands of electrode paste and cream are not appropriate for infants. Other brands of these substances are specifically designed for use with certain types of patients (e.g., infants or persons who are highly allergic). The author many years ago had a very concerning experience following the application of surface disc electrodes with a severely burned child who was receiving massive doses of potentially ototoxic drugs to prevent potentially fatal infections. The child was very ill and unable to be evaluated behaviorally. He underwent an ABR assessment of auditory sensitivity at bedside in a burn intensive unit to determine the extent of hearing loss. Within an hour after I applied conductive paste to the electrode sides on the grafted skin, the patient developed an enormous hematoma (subdermal collection of blood) at each electrode site. As soon as ABR assessment was complete, I had left the hospital unaware of the complication associated with the electrode cream. Without relating all the worrisome details, the patient's attending physician was extremely upset at the child's unusual response to the electrode cream, fearing a systemic anaphylactic reaction that might adversely affect the child's already unstable physical condition. Upon request by the physician, I attempted to determine from material printed on a tube of the paste the ingredients, but none were specified. I then called the manufacturer, explained the situation, and asked for a summary of the ingredients in the paste. The manufacturer, however, would not divulge the information. Fortunately, an hour or two later when I again made contact with the child's physician, the hematomas had resolved and there was no change in the child's health status.

The moral of this exciting little story is to always read closely fine print on any substance that will come into contact with a patient about appropriate precautions and contraindications. In the case of the severely burned patients, for whom the audiologic monitoring with ABR was essential for potential hearing preservation, I began to routinely apply electrodes for ABR measurement with alligator clips to skin graft staples placed in the proper locations (Fz, Fpz, and in each earlobe) by medical personnel. The new arrangement for electrode placement actually saved considerable time, yielded consistently acceptable interelectrode impedance (i.e., < 5 K ohms for absolute impedance and < 2 K ohms relative difference in impedance between any two electrodes in a pair). Most important, however, the alligator clip and skin staple arrangement eliminated all risk to the patient associated with electrode application.

A review of the literature revealed multiple references to dermatological reactions secondary to topical use of electrode paste (Johnson, Fitzpatrick, & Hahn, 1993; Mancuso et al., 1990; Wheeland & Roundtree, 1985; Wiley & Eaglstein, 1979; Zackeim & Pinkus, 1957; Zurbuchen, LeCoultre, Calza, & Halperin, 1996). Curiously, the original 1935 report of a skin reaction to calcium-based substances involved an Austrian ice cream maker who developed papules (a red elevated area on the skin) on his feet and legs after repeated exposure to a concentrated calcium solution used to freeze the ice cream. The papules on the skin of the ice cream maker more than seventy years ago were essentially the same problem I encountered with the burn patient during ABR measurement. In addition to the references cited, published in the English language, there are articles published in other languages. Much of the adverse experience with electrode paste was reportedly from EEG recordings in children, but there are a handful of papers describing skin reactions on the forehead and earlobes during measurement of auditory evoked responses. Focal (circumscribed) calcification in the dermis (skin), referred to as calcinosis cutis, can be caused by percutaneous (surface of skin) exposure to substances (e.g., fluids, solutions, gels, pastes) containing calcium or calcium chloride. Microabrasions, tiny scratches in the surface of the skin are, of course, purposefully produced in the conventional approach for preparing electrode locations by scrubbing the skin with a gritty substance. The skin reactions typically are evident within hours after the ABR. Factors contributing to adverse dermatological complica-

tions with electrode paste include the presence of calcium (calcium chloride), prolonged exposure to the substance (> 6 hours), and age (they are more likely in children).

The occurrence of calcihosis cutis during ABR measurement, although rare, can be minimized by thoroughly cleaning the skin immediately after the evoked response procedure to remove all traces of the conducting substance, avoidance of skin abrasion during preparation of electrode placement, and regular use of electrode conducting substances that do not include calcium as an ingredient. Aggressively abrading the skin before electrode placement also introduces the possibility of exposing the patient to risk of infection. The risk of infection is increased with the application of reusable electrodes that, while clean, are not sterilized. There is also a slight possibility of introducing infection via the percutaneous route with the use of commercially available abrasive pads, rather than a commercially available gritty liquid as the pads are, typically, not sterile.

The other question is whether electrode sites on children who require sedation for evoked response assessment (usually ABR or perhaps ECochG) should be prepared before or after the sedative is administered. Nuances of ABR measurement in infants and young children, including setup, electrode placement, and variations in the test protocol, are covered in Chapter 8 ("Frequency-Specific ABR and ASSR"). It seems logical to prepare the skin, and perhaps even attach the electrodes, before the child is sedated so as not to wake him or her with physical stimulation just before the assessment begins. This physical contact prior to or immediately after the sedative is administered, however, may agitate the child and reduce the likelihood of effective sedation. Also, a highly active child, even an infant, has an almost uncanny ability to grasp electrode wires and rip them off. In the process, hair may be painfully pulled and the child becomes more upset and active. On the other hand, waiting until the child has fallen asleep to prepare the skin permits accurate and complete electrode attachment if the child is adequately sedated. On the other hand, physical stimulation (especially scrubbing the skin prior to electrode placement on the earlobes) often arouses the child who is not completely asleep. In the final analysis, the question about when to prepare for electrode placement is based on clinical preference and clinical judgment at the time. Under ideal conditions (the child is to be given the full dose of sedative in a quiet test environment and has not shown prior sedation difficulty), I will aggressively prepare the electrode sites before sedation. Electrodes are then attached after sedation, with the child sleeping, with the expectation that the child will be aroused somewhat when the electrodes make contact with the skin. Of course, when children are to be anesthetized for ECochG and/or ABR measurement, electrode application can be completed after anesthesia is complete.

CONDUCTING PASTE, GEL, OR CREAM. | The foregoing discussion of skin preparation and electrode placement contained several references to the use of paste versus gel. Actually, three substances are available for application to the skin of nondisposable (i.e., reusable) types of electrodes. Advantages common to each of the substances include increased conductivity for evoked response activity and facilitation of lower inter-electrode impedance. The least viscous and most like liquid like substance is gel. Gel, easily squeezed onto the medial (skin side) surface of a disc electrode, is typically water-soluble. Some brands of gel are specially designed to avoid irritation to sensitive skin and staining of clothing. Electrode cream has properties similar to gel, and typically includes electrolytes adjusted to the pH of the skin. Adhesion of disc electrodes to the skin is most effectively accomplished with conductive paste. Typically white, electrode paste forms a relatively tight seal between the skin and the electrode to keep the electrode in place even without tape. Any of these three conducting substances is appropriate with disc electrodes, but the paste is particularly well suited for electrodes used on sites over the scalp (e.g., Fz, Cz, Pz, C3, and C4) for measurement of cortical auditory evoked responses.

COLLODION. | Application of electrodes with collodion is relatively time consuming, but results in firm and durable connections and minimizes artifacts. Preparation of the electrode site is done as described above. Then, the electrode is held on the location with an instrument (e.g., stylus) and collodion is spread around the rim of the electrode and onto adjacent skin. The collodion is left to dry (an air blower or hair blower hastens the drying). This secures the electrode. Conducting paste or gel is then injected into the hole in the center of the electrode. After testing, the electrode is removed (collodion dissolved) with acetone. A possible complication of collodion occurs when there is a leak in the tube. Collodion may then escape and be inadvertently dripped on the patient or clothing.

ELECTRODE REMOVAL (AFTER THE EVOKED RESPONSE PROCEDURE). | Alcohol preps are useful in removing electrode paste from the skin after testing, although a warmly moist washcloth, a paper towel, a piece of gauze, or commercially available disposable cloths designed for diaper changing work (perhaps with lotion) function equally well without irritating or drying the skin. Acetone, employed for cleaning up collodion, is somewhat hazardous and not advised for clinical use. In the neonatal or surgical ICU and OR, acetone would quickly erode plastic (e.g., plastic tubing used for arterial lines, nasogastric tubes, oxygen tubes). Reuseable electrodes should be cleaned with disinfectant soap and water, and then dried, immediately after use. An old toothbrush (sterilized and no longer used for oral hygiene) is handy for cleaning electrode paste, cream, and gel from the concave portion of disc electrodes. During cleaning, a finger should be used to support the electrode to minimize torsion and prevent breakage of the electrode lead (wire). Reusable metal electrodes should then be properly disinfected. With

proper care, reusable disc electrodes will provide many months, and even years, of reliable service.

DISC ELECTRODES. | The conventional electrode design employed since the advent of clinical application of auditory evoked responses is the disc- or cup-type electrode ("C" in Figure 3.8). The electrode disc is available in adult or pediatric sizes (10 mm or 6 mm) and is made of a metal or metal alloy, such as gold, silver, or silver coated with silver chloride (AgCl). The disc has a hole in the center of the cup and is integrated with a lead or wire of 1.0 m or 1.5 m that ends with a DIN pin. Some disc electrode designs feature a reinforced molded hub near the disc to make it easier to apply to the skin and to prevent damage to the solder joint between the disc and electrode wire (Figure 3.8). Electrode wires are available in a variety of colors. The cost of reuseable metal electrodes is about $7 to $10 each. Extension cables are available to increase the distance from the electrode on the patient to the electrode box. It is important to keep in mind, however, that electrodes function like antennae in electrically hostile test environments, and longer electrode leads increase the likelihood of picking up unwanted electrical interference.

EAR CLIP ELECTRODES. | Ear clip electrodes are a variation of the disc or cup electrode design (see "C" in Figure 3.8). Two discs or cups are mounted in a spring-type device, then connected to a typical lead or wire ending in a standard DIN pin. Following preparation of the skin on both sides of the earlobe (as described above), a conducting substance (gel, cream or paste) is applied to both of the discs, and the clip is placed on the earlobe (see "D," "E," and "F" in Figure 3.11). Because the force of the spring maintains steady pressure of the disc against the skin, tape is not necessary. In fact, adhering paste is also not necessary, so gel is adequate as a conducting substance. Ear clip electrodes also are available in different metals (e.g., gold, silver, silver chloride), but they are always sold in pairs and with leads in two colors—red for the right ear and blue for the left ear. Depending on the vendor, a set of two ear clip electrodes costs about $50 to $60. Ear clip electrodes are cleaned with the same technique described above for the conventional cup electrodes. In the author's experience with this electrode design over the past twenty years, the ear clip electrode offers at least one-half dozen distinct advantages for routine clinical use: (1) amplitude for the AP component of the ECochG and ABR wave I is increased by about 30 percent with earlobe versus mastoid placement; (2) for bone conduction ABR recordings, earlobe (versus mastoid) placement increases the distance between the electrode and the bone vibrator, thus reducing electrical artifact; (3) consistently low inter-electrode impedance is enhanced by the firm pressure against the skin and by the doubling of surface area (i.e., two discs rather than one are connected to the lead); (4) tape is not required in applying the electrode; (5) if the electrodes are pulled off during recording, as they may be with restless children, replacement is simple and reliable; and (6) with proper care the electrodes can be reused for literally hundreds of ABR recordings, resulting in low long-term cost.

DISPOSABLE ELECTRODES. | There are now a variety of designs for and manufacturers of disposable electrodes ("A" and "B" in Figure 3.8). Initially designed for use with newborn infants for universal hearing screening applications, disposable electrodes are relied upon by some clinicians for ABR recording in other patient populations. Skin preparation for application of disposable electrodes is not different to the foregoing description of the preparing for placement of disc electrodes. Commercially available disposable electrodes usually are made of foam or cloth and include within the center of the skin-side surface (recording area) a small quantity of conducting gel surrounded by adhesive glue-type substance. Disposable electrodes are available in several basic shapes (i.e., round, square, or rectangular) and are generally manufactured with silver/silver chloride gel within the recording area. There are two general disposable electrode designs. One is a single integrated design in which the electrode is connected to a lead or wire, with the entire piece discarded after use ("A" in Figure 3.8). The disc area is relatively small (about 20 to 25 mm), and the electrodes are sometimes manufactured in sets of three or four. The other design consists of individual disposable electrodes, shipped in sealed sterile enclosures, that include a snap in the center or off to one side. The disposable electrode is connected to a reuseable snap lead (wire) or alligator clip lead wire (see "B" in Figure 3.8). There are three obvious advantages of the disposable electrode design: (1) application to the skin without first applying a conducting gel, cream, or paste; (2) adherence to the skin without tape; and (3) the contribution to infection control offered by the disposable design. Disadvantages include cost for replacement ($.25 to $.75 per electrode) and limited selection of materials (e.g., not a variety of metal alloys) and design (e.g., no ear clip style). Each clinician will need to decide which general electrode design—reusable disc electrodes or disposable electrodes—is preferable given the evoked response to be recorded, the patient population to undergo recording, and the clinical application of the evoked response recording.

EAR CANAL ELECTRODES. | The most common type of ear canal electrode used clinically is the TIPtrode design (shown as "D" earlier in Figure 3.8), available for purchase from most manufacturers of evoked response instrumentation. The TIPtrode is a combination earphone and electrode consisting of a foam (polyurethane) insert ear cushion covered with gold foil. The TIPtrode is coupled to special acoustic tubing that connects the insert ear cushion to the transducer. The acoustic tubing (250 mm) includes an alligator clip design at the end that couples to the TIPtrode. Sound travels from the transducer down the acoustic tubing to the ear as with any insert earphone. Gold foil–covered TIPtrode cushions

are available in two sizes—adult and pediatric (13 mm and 10 mm). The pediatric size is optimal for any patient with smaller ear canals, including women. The cost for one set of TIPtrodes is about $4.00 to $4.50. The gold foil covering the TIPtrode insert ear cushion is connected to a conventional electrode wire with an alligator clip device (refer to Figures 3.6 and 3.8). Bioelectric activity evoked to acoustic stimuli (e.g., components of the auditory evoked responses like ECochG components or wave I of the ABR) is conducted from the ear, auditory nerve, and other auditory structures to the TIPtrode via the walls of the external ear canal. The TIPtrode insert cushions are only used with one patient, whereas the acoustic tubing and alligator clips are reused.

For placement of ear canal electrodes, such as the TIPtrode, place a small amount of abrasive liquid onto a clean cotton swab (shown in Figure 3.12). With direct lighting, and after otoscopic inspection to verify that the ear canal is clear and a brief explanation of the procedure to the patient, the outer ear is gently pulled upward and backward. This maneuver tends to straighten and enlarge the outer portion of the ear canal meatus. Then, the walls of the outer portion of the ear canal are prepared by scrubbing vigorously with the cotton swab in a circular motion. Care is taken to keep the cotton within sight. The use of conducting gel or paste is not necessary with the TIPtrode. In fact, use of conducting gel is often counterproductive, as it often causes the TIPtrode to gradually slip out of the ear canal. In the author's experience, the technique just described will routinely produce interelectrode impedance values well below the acceptable limit (5000 ohms) and comparable to impedance for other surface electrodes. In the interest of aural hygiene, ear canal electrodes, such as the TIPtrode, should only be used one time. Furthermore, the conducting property of the metal foil appears to dissipate with use, particularly in combination with abrasive liquids. Inter-electrode impedance for the TIPtrode is generally unacceptably high upon second application.

TYMPANIC MEMBRANE ELECTRODES. | As with the ear canal electrode type, it is important to first inspect the ear canal prior to insertion of tympanic membrane electrodes. Appropriate personnel should remove excessive cerumen or debris within the external ear canal before the electrode is placed. After preparing the tip of the electrode with a small amount of conducting gel, the electrode is slowly and carefully inserted into the ear canal. It is very important to use conducting gel rather than paste with the tympanic membrane technique. Within minutes after electrode application, conducting paste hardens and adheres to a surface. Clearly, it would be undesirable for the electrode tip to adhere to tympanic membrane as removal would be painful for the patient and would put the patient at risk for injury. During the insertion of the tympanic membrane electrode, the patient is instructed to report any sensation, including tickling, discomfort, or pain. At the least, the ear canal should be under direct lighting. Electrode insertion with the aid of a microscope is certainly appropriate, but not essential. The electrode is inserted until the patient reports a pressure sensation and/or hears a tapping sound. At that time, the clinician will often sense a slight resistance during insertion. Inter-electrode impedance is then measured. It is not uncommon for inter-electrode impedance to be rather high (> 5 to 10 kohms) following placement of the electrode, as the surface of the tympanic membrane cannot be prepared. The electrode lead is secured, with either tape or by insertion of a compressed foam plug.

SUBDERMAL NEEDLE ELECTRODES. | Subdermal electrodes offer the dual advantages of stability for long-term AER measurements and consistency in interelectrode impedance. They are well suited for special applications of AERs or nonauditory clinical neurophysiology, such as neurophysiologic monitoring during surgical procedures that put the auditory system or facial nerve at risk. The author's preference for needle electrodes is either a disposable or reusable subdermal stainless steel needle with a 12 mm uninsulated shaft and 0.4 mm diameter, a beveled tip, and a conventional cable length (1 meter). Subdermal needle electrodes are also constructed of platinum iridium, with the option of insulation along the shaft (uninsulated tip). Electrode cables for the disposable

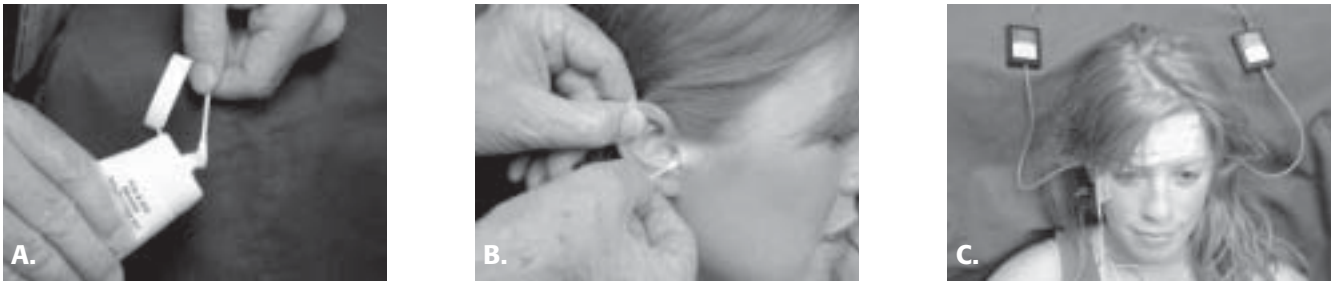

FIGURE 3.12. A figure showing the preparation for, and application of, a TIPtrode electrode used in clinical measurement of the ECochG and ABR, including application of abrasive substance on a cotton swab (A), preparation of the skin in the external ear canal (B), and electrodes and transducers in place (C). Note that the electrodes and transducers remain separated.

and reusable versions of the subdermal needles are available in a variety of colors. The value of color-coding placement of electrodes in auditory evoked response measurement is noted below. Disposable electrodes are sterilized and packaged individually, whereas reusable needle electrodes typically are purchased in packages of 5 or 10. *It is important to note that reusable subdermal needle electrodes must be sterilized before each use (e.g., gas sterilization is available in hospitals and medical clinics).* Needle electrodes can be used for an auditory evoked response recording when the patient is first anesthetized. Needle electrodes present at least three distinct advantages for routine use clinically in such cases. First, application is faster as there is little skin preparation. The skin at the electrode site should be wiped vigorously with an alcohol swab before the electrode is inserted almost horizontally under the skin, then the electrode lead (wire) is secured with a piece of tape. Second, needle electrodes tend to be more stable during prolonged auditory evoked response measurement than disc (surface) electrodes. And, finally, inter-electrode impedance is adequately low and invariably balanced, even though no valuable test time was consumed in scrubbing the skin. The two potential (and highly unlikely) health risks posed by needle electrodes are spread of disease by an unsterilized needle and needle breakage, i.e., a portion of the needle remains under the skin. Of course, placement of subdermal needle electrodes must be considered an invasive procedure. Although complications are very unlikely, subdermal needle insertion should always be done by appropriate medical personnel or by experienced nonmedical personnel with medical support readily available. Other types of needle electrode designs available commercially for auditory evoked response recording and used by some clinicians include longer (e.g., 25 mm) monopolar needles and disposable corkscrew electrodes.

TRANSTYMPANIC MEMBRANE ELECTRODE. | The specific technique for placement of transtympanic (TT) membrane electrodes varies depending on the type of needle that is used. The following description applies to the transtympanic placement of a subdermal needle electrode that was just described, rather than a longer needle electrode, as often reported in the literature and sometimes applied clinically. In the clinic, prior to insertion of the needle, the tympanic membrane is typically anesthetized with a Phenol (89%) swab. A microscope is used for viewing the tympanic membrane. The patient usually describes a burning or tingling sensation as the Phenol reaches the eardrum. In the operating room, when ECochG is applied during neurophysiologic intraoperative monitoring, the transtympanic membrane electrode placement is performed after the patient is under general anesthesia. A physician (e.g., otologist) places the needle electrode onto the promontory under an operating room microscope. The use of subdermal needle electrodes in transtympanic recording of the ECochG, including the technique for insertion, is described in Chapter 4, with clinical applications reviewed Chapter 5.

GENERAL ELECTRODE PLACEMENT. | The pin on any electrode lead wire is inserted into an electrode connection strip or box (see Figure 3.13). There are different types of electrode boxes. Some are relatively simple with receptacles for connectors for three or five electrodes (receptacles for a single channel of one noninverting, one inverting, and one common ground electrode) or two sets of noninverting and inverting electrodes with a common ground). Simpler electrode receptacles may be labeled with various symbols (e.g., A+, A- and C; G1, G2, and ground ["gnd"]; active, reference, and ground). Others are more sophisticated preamplifiers with electrode locations displayed on a head-shaped diagram and labeled according to the International 10–20 system

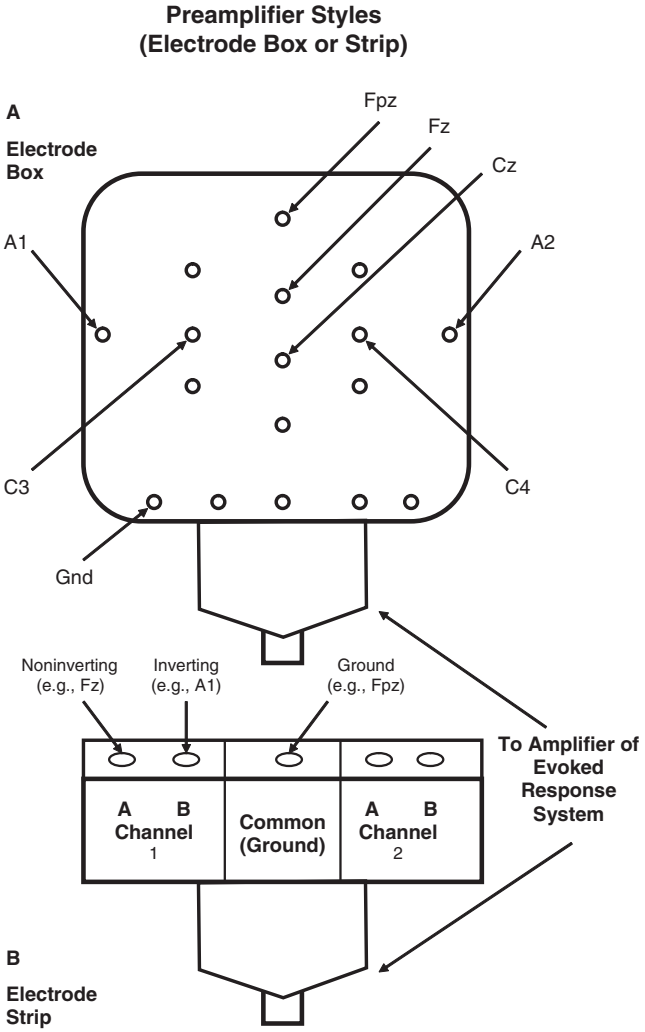

FIGURE 3.13. An electrode box for placement of electrodes in a variety of locations used in recording auditory evoked responses (A). An electrode strip with receptacles for noninverting and inverting electrodes for two recording channels and a ground electrode (B).

(Figure 3.9). With these devices, individual electrodes may be selected and changed via the computer keyboard. It is, of course, important to verify that each electrode wire pin is inserted in the proper slot before evoked response recording. A simple color-coding system is useful to facilitate consistently proper electrode placement. For ABR measurement, the author recommends the use of a different color for each site. Being among 10 percent of the male population that is color deficient (i.e., red-green "colorblind"), I always utilize the same primary colors for each of the electrodes, namely, a bright and light color (e.g., yellow or white) for the noninverting (Fz) electrode, red for the right earlobe or TIPtrode, blue for the left earlobe or TIPtrode, and a dull and dark color (e.g., gray, brown, or black) for the common (ground) electrode. The set of four reusable or disposable electrodes, each a different color, can be braided or tied loosely into a few knots to reduce the likelihood of electrical interference. Because the colors are so different, it's possible to verify which electrode site is plugged into which electrode box receptacle, even though the wires are braided or tied, and even in a darkened test room. Recall from the discussion above that it is possible to use one electrode for two channels, or to "link" any pair of electrodes (such as two earlobe electrodes) with "jumper cables" (short wires have a pin at each end and also a receptacle for an electrode pin at the top).

ELECTRODE ARRAYS. | The combination of two recording electrodes forms an electrode array or montage. For routine measurement of the ABR, a single-channel electrode array is recommended (Fz-Ai or ipsilateral earlobe). Under some clinical circumstances, such as bone conduction ABR measurement, the addition of a second channel (Fz-Ac or contralateral earlobe) is helpful for confident identification of wave I. The ipsilateral electrode array (Fz-Ai) combination of electrodes is most likely to produce clear waves I through V and to facilitate identification of wave I (present in the ipsilateral and absent in the contralateral arrays). Furthermore, digitally subtracting the contralateral array waveform from the ipsilateral array waveform yields a "derived" horizontal waveform (described and illustrated in Chapter 7). Use of a noncephalic inverting electrode, truly a "reference" electrode has definite electrophysiologic rationale and may, in some cases, contribute to the resolution or identification of selected wave components. As with any AER measurement strategy, a clinician should consistently utilize customary stimulus and acquisition parameters (for the facility) in initial recordings, but then modify these parameters as the need arises during the assessment to enhance the quality of AER waveforms.

Electrode sites used in AMLR measurement have undergone changes within recent years. Formerly, a midline (Cz or Fz) noninverting electrode site was used almost exclusively. Currently, the AMLR is recorded with multiple scalp sites for noninverting electrodes. What about the inverting electrodes? As just noted, some investigators continue to record AMLR with a two-channel array characterized by a common midline noninverting electrode and inverting electrodes on the ears ipsilateral and contralateral to the stimulus. Such an array is selected to enhance the different contributions to the waveform by the ipsilateral versus contralateral ear. With the multiple scalp electrode technique (noninverting electrodes at Fz, C5, and C6), on the other hand, an attempt is made to eliminate the ipsilateral versus contralateral ear contribution by "linking" these two electrodes. That is, the inverting electrode leads from each ear are usually plugged into a jumper lead connecting the amplifier inputs for each inverting electrode. The result is a "balanced reference" equalizing contributions of the ears to each of the scalp electrode arrays. Thus, differences among waveforms for the two or three scalp electrode arrays can be attributed to hemispheric, or CNS, factors, rather than contributions from the ear or differences in the orientation of the array with respect to the stimulus side.

Electrode Box

Electrodes are usually plugged into an electrode box that is connected to the amplifier with a shielded cable. Electrode boxes are available in different shapes and sizes (Figure 3.13). There may also be, at this stage, a preamplifier. An electrode box has minimally three receptacles (also called jacks), one each for the noninverting, inverting, and ground electrodes. This constitutes one recording channel. Most electrode boxes allow for at least two channel recordings with five or six electrode receptacles. The receptacles may be arranged in a single row, two or more rows, or in the shape of a head. Channels on electrode strips are sometimes indicated by numbers (e.g., Channel 1, Channel 2) or letters (A, B, C, . . .). Labels for the individual receptacles for each channel also vary. They may be color coded or referred to by polarity of the amplifier input (e.g., A+ for the positive voltage electrode in channel one, A– for the negative voltage inverting electrode in channel one, and C for the common [ground] electrode, with a similar format for the B or second channel). The term G (originating from the use of electrode grids) may be used to refer to electrode receptacles, so that G1 is the first electrode (noninverting), G2 is the second electrode (inverting), and so forth. Box type preamplifiers have electrode receptacles with the 10–20 International Electrode System labels (e.g., Cz, Fz, A1), while a few others on the electrode box are reserved for miscellaneous electrodes and given numbers or other labels (e.g., X1, X2).

For electrode boxes with receptacles for electrode placements at a variety of scalp locations (see Figure 3.13), the electrode sites to be used with a specific auditory evoked response recording are selected with evoked response system software. The protocol for a two-channel ABR might, for example, call for electrodes at Fz, A1, and A2 locations, and a ground (common) electrode. These labels would be selected from the collection parameters or settings page of the

evoked response program. With electrode strips, the physical location of the electrode pin determines the actual electrode input (e.g., channel 1, + electrode). Each channel on the electrode strip has a receptacle for a noninverting ("positive" or "active") electrode. To avoid the need for placing two noninverting electrodes on the patient (one for each channel), the receptacles can be connected or linked with a short "jumper" cable consisting of both electrode pins and receptacles, i.e., male and female DIN connectors. The jumper cable is rather short (about 15 mm), with one end plugged into the noninverting electrode input (#1 or + input) for one channel, and the other end is plugged into the corresponding other input for the second channel. Then, the pin for a single noninverting electrode (e.g., at the Fz site high on the middle of the forehead) is inserted into one of the jumper cable receptacles (it doesn't make any difference which one). Jumper cables for linking electrodes can be purchased from most manufacturers of evoked response systems, and a few extra cables should always be available among evoked response supplies in a clinic. We will describe another application of the jumper cable in the review of auditory middle latency response (AMLR) measurement in Chapter 11 (see "Electrode Sites" in the section on "Acquisition Parameters").

Naturally, the first step in adequate amplification is plugging the electrodes in properly. Without careful attention to this task, however, mistakes are sure to occur. Troubleshooting guidelines, to prevent serious consequences from this technical error for specific types of auditory evoked responses, are described in subsequent chapters. Current evoked response systems permit keyboard control of electrode connections. With these evoked response systems, it is often possible for electrode switching (from one array to another) to be automated by simple programming. This feature can potentially eliminate some of the more frequent technical errors in AER assessment.

Electrophysiologic Amplification

Usually, the term *amplifier* suggests a device that increases the strength of a signal (acoustical or electrical). A simple example is found in every radio. Increasing the gain or amplification makes music or talking louder. *Gain* is technically defined as the ratio of the voltage of the signal at the output of the amplifier (after amplification) to the voltage delivered to the input. An amplifier is a crucial component of an evoked response system because AERs generated by the cochlea, eighth nerve, or brain are very small (as little as 1 millionth of a volt). The average amplitude for ABR wave V, for example, is about 0.5 microvolt (μvolt), i.e., one-half of one-millionth of a volt. AERs must, therefore, be amplified substantially before they can be processed by a signal averaging computer and displayed on an oscilloscope or computer monitor screen. As an example of AER amplification requirements, in ABR recording gain is typically set at X100,000. Since the amplitude of the output-to-input is expressed as a ratio, and amplification is usually expressed in order of magnitude of 10, gain is sometimes described in a logarithmic unit that reflects these characteristics, the dB (dB = X log 10 gain). A gain of 10 would, for example, be equivalent to 20 dB and the typical ABR gain of 100,000 would be 100 dB.

There are two characteristics of an amplifier that have a direct influence on successful AER recording. One is input impedance, simply defined as opposition to alternating current flow, specifically impedance across the amplifier inputs. Optimally, input impedance of the amplifier is comparable to or higher than the electrode impedance for AER recording. A serious problem develops when there is an imbalance in electrode impedance, with one electrode having higher impedance than another.

COMMON MODE REJECTION (CMR). | Common mode rejection is a vital function of the amplifier. It is also an important concept in understanding how relatively tiny AER voltages can be detected in the midst of a wide variety of other electrical signals, many with far greater amplitude. As a first step toward this understanding, several terms should be clarified. Two electrodes placed at different locations on the head (e.g., the high forehead in the midline [Fz] and an earlobe) will presumably each detect the same amount of electrical interference (electrical activity that does not include the response) that is in the region of the head (refer to Figure 3.14). This interference is common to, or the same for, each electrode. The differential preamplifier, which is a component of most evoked response systems, reverses polarity (positive or negative sign) of inverting electrode input voltage and adds it to noninverting electrode input. This is in effect a subtraction process. In this way, any activity that is the same as detected at each electrode is eliminated (rejected), as shown schematically in Figure 3.14. Therefore, one of the electrodes (amplifier inputs) is called the inverting electrode and the other is the noninverting electrode. This is the accurate, and preferred, terminology for describing electrodes, as noted previously in the discussion of electrode terminology.

If each electrode recorded exactly the same AER activity, then common mode rejection would subtract away the response. To demonstrate this point, record an AER with two electrodes (noninverting and inverting) placed next to each other, for example, both on the forehead. The result is nearly a flat line. All AER activity is detected similarly by each electrode and is eliminated by the common mode rejection process. However, with one electrode on top of the head and another located near the ear, the response detected by each is not the same but, in fact, very different. Early components of the ABR, in particular, are usually of opposite polarity. Subtracting the activity detected at the earlobe electrode from activity at the vertex electrode not only reduces noise interference, but it actually increases amplitude of some ABR components. However, if any AER activity as detected by the two electrodes is the same, it will be lost

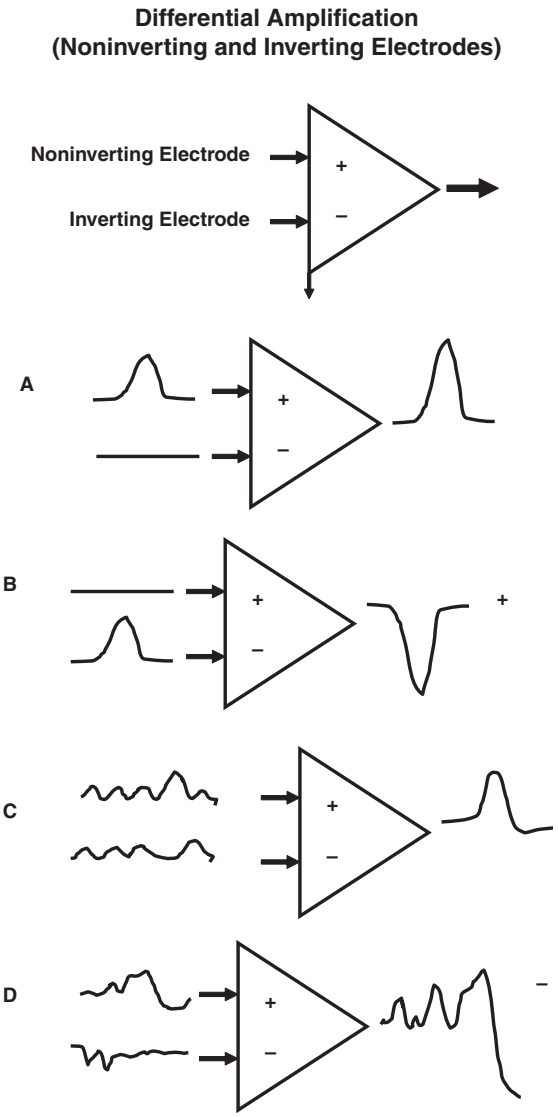

FIGURE 3.14. A schematic representation of the process of differential amplification that used in auditory evoked response measurement.

from the recording. With a cephalic electrode (located somewhere on the head) and noncephalic electrode combination, interference common to each is subtracted out, leaving only the response detected by the cephalic electrode. While there is no augmentation of early ABR components, which is a disadvantage, there is also no inadvertent rejection of portions of the response, which is a distinct clinical advantage. Recording far-field AERs with two relatively closely placed electrodes, each at the same end of the generator dipole, such as the vertex and forehead for ABR, is clearly not advised (see Chapter 7 for examples of this and numerous other technical faux pas in ABR recording). The effectiveness of common mode rejection is usually expressed in terms of a ratio of the amplifier output (the electrical activity that remains after amplification) with only one input (i.e., without the benefit of the subtraction process) to the amplifier output when both inputs are the same. Usually the CMR ratio is more than 10,000, meaning that activity detected similarly by both electrodes, such as electrical interference, is more than 10,000 times smaller than the amplitude of activity detected by the noninverting electrode. The ratio is often expressed in decibels, which is a logarithmic value. A CMR ratio of 10,000 would be equivalent to a value of 80 dB. For example, a ratio of 10:1 is 10 dB, 100:1 is 20 dB, 1000:1 is 40 dB, and so forth.

ARTIFACT REJECTION. | A necessary feature in evoked response instrumentation is the capacity for viewing incoming electrical activity. The electrical activity detected by the electrodes is a combination of EEG, AER, and unwanted electrical interference, in a relatively "raw" state, before it is filtered or averaged. Even at this early stage, the input has been subjected to the common mode rejection process and to amplification. One might say that an AER is only as good as the raw EEG within which it is embedded. Ongoing, or at least periodic, inspection of the unaveraged electrical signal can provide clinically valuable information on subject state (quiet or active, awake or asleep) and the amount and type of electrical interference influencing the recording. With a little experience, the clinician can quickly differentiate quiet artifact-free EEG from EEG contaminated by general patient movement, neuromuscular artifact, electrical interference at 60 Hz, or another discrete frequency or high-frequency electrical interference. The clinician may be alerted to the presence of interference by the artifact rejection indicator; however, visual inspection of the raw incoming signal is a more effective approach for determining the type and, perhaps, the source of interference. This information can then guide attempts at reducing or eliminating the problem.

An artifact in AER recording is, by definition, electrical activity that is not part of the response and should not be included in analysis of the response. The artifact may be electromagnetic and generated from an external (nonpatient) source (e.g., earphones or an electrical device) or it may be electrophysiologic, originating from the patient, such as neuromuscular potentials related to patient movement. There are three main approaches for reducing the negative influences of artifact on AERs. The first, and best, is to determine the source of the artifact and eliminate it. For example, it might be possible, by process of elimination, to identify an X-ray view box as the source of serious electrical artifact that totally precludes AER recording. By turning off the view box, the artifact will disappear and test conditions are adequate. When excessive patient movement is the source of neuromuscular artifact, the patient may be given a sedative and fall asleep. Testing then proceeds without difficulty. Another approach for dealing with artifact is to modify test parameters, such as filter settings, electrode arrays, and number of sweeps. Practical guidelines for management of these

sources of artifact in AER measurement are suggested in subsequent chapters. The third approach for minimizing the deleterious effect of artifact on AER recording is a technique known simply as artifact rejection. With earlier generations of signal averaging devices, the tester was required to constantly keep vigil over the ongoing EEG as displayed on an oscilloscope and manually pause the averaging process during periods of excessive artifact. This arrangement is not ideal because it necessarily occupies tester attention and time during the AER assessment session, time that could be devoted to record keeping, online inspection of the response, and analysis of AERs as they are signal-averaged. Also, in the time it takes the tester to determine the presence of artifact and pause the averaging process, artifact contamination of the response may have already begun.

Automatic artifact rejection is a feature on most evoked response systems. The simplest artifact rejection design is based on the sensitivity setting of the amplifier. Any signal detected by the electrodes that exceeds a designated preset voltage is not sent on to the signal-averaging device. This is an effective means of eliminating from the averaging process occasional very high-voltage sources of artifact. In theory, then, only relative pure signals (within an acceptable voltage range) are averaged. These are, of course, not necessarily AERs but are at least within a voltage region that AERs usually are found. To be effective clinically, an artifact rejection system must not permit any unwanted electrical signal to enter the averaging process. One way to accomplish this is to keep each analysis time period in memory, before it is sent on for averaging, in order to complete an artifact detection process. If no artifact is identified, the EEG (maybe including AER activity) is passed on to the signal-averaging device, but if artifact is present, the entire analysis time period (which was triggered by one stimulus) and maybe the preceding and following time periods are erased from memory.

Artifact rejection devices are very useful, but not an answer to every artifact problem. Two common clinical limitations are the inability to make progress with averaging because of almost continuous artifact rejection and the obvious contamination of an waveform that is being averaged with artifact despite the use of artifact rejection. Increasing the sensitivity of the amplifier (increasing amplifier gain) to solve the second problem will also increase the sensitivity of the artifact rejection process and perhaps create the first problem.

ALTERNATIVE TECHNOLOGY. | Conventional systems record AER with an interface module with a differential amplifier and a serial or USB port. The electrode lead wires are connected to the differential amplifier, and the computer is connected to a serial or USB port. This connection may introduce electrically conducted noises into the AER amplifier from the computer and the power line. In the Integrity™ system from Vivosonic Inc., communication between the interface module and computer is performed through a wireless interface module, the VivoLink™ employing Bluetooth® wireless communications. This eliminates the electrical path between the computer and AEP amplifier, and as a result eliminates introduction of electrically conducted noises from the computer and power line. In addition, it allows for convenient recording from a distance within the Bluetooth® range of about 30 feet (10 meters): The VivoLink™ can be placed in an infant's crib, bassinet, incubator, stroller, or car seat and the computer can be placed anywhere within a 10 meter radius. In the operating room, it can be placed on or near the operating table, while the operator performing the test—for example intraoperative monitoring—can be seated away from the operating table, even in another room, and not interfere with the crew performing the operation (Sokolov, Zhang, & Long, 2005).

Filter Settings

Filter settings are chosen to eliminate unwanted nonresponse activity (electrical and muscle interference or artifact) while preserving the actual response. A principle of filtering was stated earlier in Table 3.1. Filters, simply put, selectively remove part of the bioelectrical activity from the total bioelectrical activity plus electrical activity arising from sources outside of the brain. In AER measurement, filters reject electrical energy at certain frequencies and pass energy at other frequencies. An appreciation of four points is important for appropriate use of filtering in clinical AER measurement:

1. Why filtering is employed in recording AERs.
2. How the properties and performance of a filter are described.
3. The spectral composition of each type of AER.
4. How filtering can alter each type of AER.

Appropriate selection of a filter setting, then, requires an appreciation of the spectral characteristics of noise and signal (e.g., the auditory evoked response). The ECochG and ABR have spectral energy from just below 100 Hz up to 1000 Hz, or slightly higher frequencies. Thus, for measurement of these responses clinically, filter settings of 30 to 1500 Hz or 3000 Hz will effectively minimize general EEG activity (frequencies under 30 Hz) that do not contribute to the response while still preserving the spectral energy that forms the response. AMLR, in neurologically normal adults at least, has energy predominantly in the range of 20 to 40 Hz. The longer latency responses are dominated by low-frequency energy (below 30 Hz).

Analysis of the number of waves per second in the AER waveform is a handy way of estimating some of the frequency content of the response. For example, casual visual inspection of normal ABR waveforms reveals major waves approximately every 1 ms (e.g., 1000/second or 1000 Hz) plus a slow frequency wave with a frequency of about 100 Hz (one wave/second). The safest policy clinically is to filter as little as necessary, so as to reduce the possibility of filters

contributing to distortion in the latency of components in the waveform, or even apparent components in the response that are really artifacts. Wider filter settings during data collection are desirable if evoked response instrumentation permits digital filtering after data collection, although with conventional artifact rejection options the averaging process may be slowed by the presence of unfiltered noise.

WHY IS FILTERING NECESSARY IN AER MEASUREMENT? | Filtering is a technique for enhancing detection of a signal (the AER) in the presence of background electrical noise. Noise here is defined simply as any electrical activity detected by the electrodes (from the patient or external sources) that is not auditory evoked response. Theoretically, noise with frequency content that is different from the frequency content of an AER can be filtered out of the raw electrical activity detected by the electrodes before the averaging process. It is more effective to average activity that is likely to include the response than unselected activity. The main objective of filtering is to reduce or eliminate from the averaging process nonresponse electrical activity with relatively well-defined and consistent frequency content. One example of this type of electrical noise is the normal EEG frequency region, which is below 30 Hz (including delta, theta, alpha, and beta EEG). Whenever appropriate, electrical energy in the region of 0.05 to 30 Hz is filtered out of AERs. This frequency region also encompasses electrodermal noise (0.01 to 5 Hz) and a portion of the frequency region of movement potentials (around 0.05 to 50 Hz). Another type of electrical noise targeted in routine AER filtering is neuromuscular (myogenic) activity. Electromyogenic noise may share a portion of the spectrum for some AERs (the 100 to 500 Hz region) and, therefore, cannot be entirely filtered out. However, it may also include frequencies of up to 5000 Hz. Low-pass filter cutoffs of 1500 or 3000 Hz minimize interference with AER measurement by activity in the higher frequency range.

PROPERTIES OF FILTERS. | Filter-related terms and concepts are illustrated in Figure 3.15. High-pass filters reject lower frequency energy and allows higher frequency energy to pass through. Low-pass filters function in just the opposite way. In combination, high- and low-pass filters can be set to pass a band of frequencies. A band-pass filter rejects energy below a certain cutoff and above a certain cutoff, passing energy for a band of frequencies within these two limits. Band-pass filtering is commonly employed in AER measurement. One essential property of a filter, then, is the frequency at which energy is rejected versus passed. This is often referred to as the cutoff frequency. There are two somewhat confusing terms in describing filters. The first is that the high-pass filter cutoff frequency is actually the lower frequency limit of the energy passed, whereas the low-pass filter cutoff frequency is the upper limit of energy passed. So, for a band-pass filter of 30 to 3000 Hz, the high-pass filter is from 0 to 30 Hz, the low-pass filter is from 3000 Hz to some upper limit (e.g., 10,000 Hz). The term "cutoff" is also misleading because it implies an either/or function, a single frequency above or below which all energy is rejected or passed. For conventional analog filters that deal with input electrical activity in ongoing nondigital form, however, the cutoff frequency is simply where energy begins to be filtered (Figure 3.15).

A common definition for the cutoff frequency is that point at which electrical energy output from the filter is decreased by 3 dB (the 3 dB downpoint). The slope of an analog filter is an important feature, because it defines the sharpness of filtering. Filters in many evoked response systems, such as the standard-phase Butterworth filter, reject energy at a rate of 12 or 24 dB/octave. The important point here for clinical AER applications is that that energy will be passed for frequencies beyond the cutoff. A common clinical example of this limitation is experienced with attempts to eliminate bothersome 60 Hz power line interference. Selecting a high-pass filter cutoff of 100 Hz would seem be a solution to the problem, because 60 Hz is well below this cutoff. Unfortunately, 60 Hz energy will not be rejected (will be passed) with a filter slope of 12 dB/octave and interference

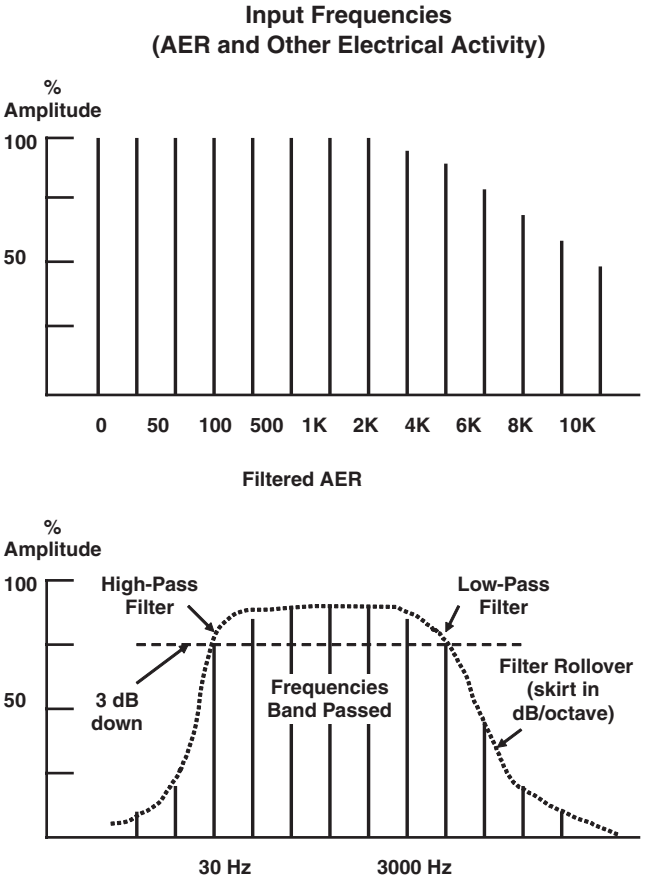

FIGURE 3.15. A schematic representation of the process used in filtering of electrophysiologic activity prior to the analysis of auditory evoked responses.

persists. It would appear that increasing the filter slope is a simple solution to this problem, that is, it would make the filter more precise. In fact, steeper slopes (e.g., 24, 48, or even 96 dB/octave) are possible for analog filters, but they cause greater distortion of the response. This point is discussed further in a later section. The optimal solution to this apparent dilemma is to digitally filter. Digital filtering permits very sharp filtering without associated distortion, particularly phase and latency distortion of the response.

60 HZ (CYCLE) NOTCH FILTERING. | Most evoked response systems provide the option for narrowband rejection, or filtering, of electrical activity in the region of 60 Hz. The objective is to selectively eliminate from the auditory evoked response 60 Hz power line interference without removing other frequencies from the response. Theoretically, then, a 60 Hz notch filter would be preferable to filtering out all frequencies below, for example, 75 Hz, which would include this interference. Such selective filtering is a questionable clinical practice for several reasons. First of all, harmonics of the electrical activity at 60 Hz interfering with AER measurement (occurring at higher frequencies) are not eliminated and may continue to contaminate the recording, limiting the effectiveness of the filtering technique. Second, any analog filtering will usually produce distortion of response phase (latency) and the purposely steep notch filter characteristics may actually cause more latency distortion than conventional band-pass AER filtering at the amplifier. Finally, for some AERs, such as the AMLR or ALR, even limited filtering around the frequency of 60 Hz will probably remove a substantial portion of the energy of the response and limit the inherent validity of the waveform.

THE SPECTRUM OF AERS. | Perhaps the most important issue in determining appropriate filter settings, and one sometimes overlooked, is the spectral composition of the AER being recorded. In the interest of filtering out unwanted electrical noise frequencies, it is possible to also eliminate part of the actual response. Clearly, "throwing the baby out with the bathwater" will not enhance AER recordings. How can the frequency composition of an AER be determined? The most accurate approach is spectral analysis of the response, made, for example, by performing a fast Fourier transformation (FFT) on an averaged waveform. Frequency content of the waveform can be assessed with an instrument designed for this type of analysis, a spectrum analyzer. Some commercially available evoked response systems also have software for AER spectral analysis.

Spectral characteristics of an AER can, without any equipment or special skills, be estimated by close examination and calculation of waveform changes over time. Examine a typical ABR waveform recorded with a relatively wide filter setting (30 to 3000 Hz). The major waves components (I, II, III, V, VI) occur at intervals of about 1 ms. Thus, the ABR would be expected to have energy in the region of 1000 Hz (1000 waves per second or 1 wave/ms). These sharper waves that occur more often appear to be superimposed on a slower wave that just about completes one cycle (it has its beginning and end) within a 10 ms time period. An event that occurs once every 10 milliseconds has a frequency of 100 Hz (100 cycles per second). Spectral analysis of the ABR also shows dominant energy in this general frequency region. Similarly, spectral composition of other AERs can be estimated by visual inspection of waveforms and extrapolation of the number of wave components per second. The AMLR wave components are found at approximately 25 ms intervals. An event occurring every 25 ms repeats itself approximately 40 times in a second, or at a frequency of 40 Hz. Clearly, the ALR and P300 have even slower frequencies. As a general rule, then, the most appropriate and effective filtering for each of these AERs preserves the frequency region of the response and excludes other frequency regions. Using band-pass filter settings from 0.1 to 50 Hz would be totally inappropriate for ABR recording since most of the response would be eliminated, but these settings would be quite adequate for ALR measurements. Conversely, a 30 to 3000 Hz filter setting is appropriate for ABR since it encompasses important frequencies in the spectrum while eliminating EEG frequencies and possible higher frequency (above 3000 Hz) artifact. This same filter setting would be very inappropriate for ALR, since the spectrum of response is primarily outside of the band-pass region (below 30 Hz) and would be rejected before the averaging process.

EFFECT OF FILTERING ON AERS. | The objective of filtering, as noted above, is to reduce the amplitude of unwanted electrical noise without altering the response that is measured. In clinical practice, however, this is probably accomplished only rarely. Often, the problem is too much rather than too little filtering. The reason for this tendency may be that excessive filtering offers a false sense of security in AER measurement. Electrical noise is often effectively eliminated with very restricted filter settings. The result is a smooth waveform that is appealing to the eye and deceptively easy to analyze. There are two potential dangers of severe filtering. First, important portions of the response are eliminated, rendering even the most meticulous waveform analysis invalid. Second, distortion products in the waveform caused by the filtering process can be mistaken for response components, perhaps the components that were removed by the filtering. Examples of these two dangers will be shown for selected AER waveforms in discussions to follow.

The second danger of filtering, response distortion, has been the topic of much investigation (Boston & Ainslie, 1980; Dawson & Doddington, 1973; Doyle & Hyde, 1981b; Glaser & Ruchkin, 1976; Lane, Mendel, Kupperman, Vivion, Buchanan, & Goldstein, 1974; Scherg & Volk, 1983). Analog filters, as just noted, produce rather complex alterations of both amplitude and phase (latency) of AERs. As a rule, all filtering reduces response amplitude. When amplitude of a

component appears to increase with more filtering, the contribution of filter ringing effects must be suspected. Filtering may, however, produce shorter latency responses (create phase lead) or prolong response latency (phase lag), depending on whether the filter is high pass or low pass, the slope of the filter, and the frequency composition of the response. There are two additional complicating factors. One is that an AER may consist of components with different spectral content (low frequency or slow components and high frequency or fast components) that are, therefore, differentially affected by the same filter. The other is that, although the distortion effects of a filter become prominent as the cutoff frequency approaches the AER frequency component, distortion of the response can be demonstrated even when the filter cutoffs are well beyond (lower or higher than) the spectral limits of the response. The end result of these two types of filter effects can be misinterpretation of AERs.

Given these limitations of conventional analog filter in AER measurement, are there other options? Weiner filtering has been proposed as one alternative (Carlton & Katz, 1980; Doyle, 1975; Walter, 1969). Weiner filtering is theoretically more precise than conventional analog filtering. It's based on previously obtained information as to which frequencies contribute to the response and which frequencies are nothing but noise. The Weiner filter emphasizes the frequency regions that contribute to the signal (the AER) and that contain less noise. Other frequencies (with weak signal and strong noise) are suppressed. In this way, theoretically, the average square error of the noise is reduced and less averaging is needed to improve signal-to-noise ratio, or SNR (Møller, 1983c). Two assumptions underlying Weiner filtering are that the spectrum of the signal and noise are defined and that signal and noise are constant during the analysis period. As noted above, these assumptions are not always valid for clinical AER recordings. Nonetheless, the overall objective of Weiner filtering is to suppress the effects of noise and thereby reduce the signal averaging that is necessary to produce a quality response. The clinical usefulness of *a posteriori* Weiner filtering is not yet documented.

Another approach is the clinical application of time varying and adaptive filters to better separate signal from noise, and then to reduce or eliminate the noise components (Wastell, 1977; Woody, 1967). Hoke, Wickesberg, and Lutkenhoner (1984) propose a filtering approach described as time- and intensity-dependent that generates no significant phase or amplitude distortion. The concept of this technique is in some respects related to time varying and *a posteriori* Weiner filtering just noted, but it is adapted to the computer demands of ABR measurement. Short-time Fourier (spectral) analysis of 128 overlapping segments of an ABR within a time analysis period (e.g., 15 ms) is computed. Uniquely, filtering is customized on the basis of the specific ABR spectrum at different times and at different intensities, rather than on a fixed overall estimate of spectral characteristics throughout the analysis period and across intensities.

Ultimately, the best overall approach for AER measurement may be the routine use of digital zero phase shift filtering, either online (prior to the averaging process) or offline (after a response has been averaged with virtually no analog filtering). Either way the AER must be converted to a digital form first, and analog filtering typically needs to precede digital filtering to avoid aliasing errors. Aliasing can occur when the sampling rate is too low with respect to the upper frequency limit of the AER or the cutoff frequency of the low-pass filter. One problem with this approach is that information in the waveform is lost. In addition, low-frequency components that are not part of the response but, rather, a product of aliasing may appear in the waveform. Reports and examples of digital filtering of AERs are noted in the discussion below. A very important clinical implication of filter effects on all AERs relates to the collection and use of normative data. There must be consistency within a laboratory in the filter settings employed in collection of normative data versus routine clinical AER measurements. Similarly, interpretation of clinical AER latency and amplitude findings in the context of published normative data is valid only if filter class (e.g., active or passive), type (Butterworth, Bessel, Chebyshev), settings, and slope are equivalent. Kalman filtering, application of a relatively new type of filter in auditory evoked response instrumentation, is described toward the end of the chapter.

ALTERNATIVE FILTERING TECHNOLOGY. | Conventional ABR filtering is usually performed after the first stage of amplification in the differential preamplifier. In this arrangement, the first stage of the preamplifier is designed to amplify a broad-spectrum signal. This is why this stage is open not only to AER signals, but also to very low-frequency physiological signals coming from the ocular activity (EOG), brain activity (EEG), and cardiac activity (ECG). Since EEG and EOG can be more that 100 times the magnitude of ABR, great care must be taken to ensure that the input stage of the recording amplifier does not become saturated, which would distort the recorded signal, and subsequent filtering would not remove the created distortion (Bell, Smith, Allen, & Lutman, 2004). Moreover, the operator may not even recognize such signal distortion, because the so-called "ongoing EEG" on the recording equipment may display no significant artifacts. While a low front-end gain has the advantage of avoiding saturation, this arrangement has a significant disadvantage in its reduced common mode rejection ratio (CMRR) and consequent increased susceptibility to noise (Spinelli, Pallàs-Areny, & Mayosky, 2003).

The conventional arrangement of filtering after amplification may also result in signal contamination due radio frequency (RF) noise coming from cellular phones, wireless networks, and other high-frequency equipment (deJager et al., 1996). Electronic amplifiers—AER differential amplifiers being no exception—will demodulate (rectify) such high-frequency broadband signals due to their nonlinearity,

causing an effective frequency shift of the radio frequency (RF) noise into the frequency range of AER. Once this occurs, no amount of low-pass filtering at the amplifier's output can remove the error. Moreover, common mode rejection, which is the major purpose of differential AER amplifiers, is typically ineffective for frequencies above 20 kHz (Kitchin, Counts, & Gerstenhaber, 2003).

An alternative approach, employed in the Amplitrode™, available as part of the Integrity™ system from Vivosonic Inc., is to filter the input signal prior to its amplification. Currently, the Amplitrode™ applies a high-pass 30 Hz filter, optimized for ABR measurement, and a low-pass RF filter prior to amplification. This technique eliminates contamination due to RF rectification as well as unwanted low-frequency physiological signals such as electro-oculography (EOG), electrocardiology (ECG), and most EEG from the measurement prior to amplification, reducing the risk of saturation in the first stage of the amplifier, thus making it possible to optimize the amplifier's gain.

Averaging

The heart of conventional evoked response systems is the signal averaging device. Techniques for averaging neurophysiologic signals introduced by Dawson in England in the late 1940s and refined by Clark and associates at MIT in the 1950s, ultimately made AER measurement clinically possible. From the outset, it is important to keep in mind that AERs can be recorded using techniques other than signal averaging. However, most of this section will be devoted to a discussion of signal averaging since it remains the commonest approach for detecting AERs in the presence of a background electrical noise. A straightforward explanation of principle of averaging was summarized in Table 3.1.

ANALOG-TO-DIGITAL CONVERSION IN AER MEASUREMENT. | After the raw EEG (which may include an AER) is amplified and filtered, it is converted from continuous analog activity to digital form. Voltage of the waveform over the course of the analysis period is sampled (measured) at a certain number of points and expressed in a number. The number of points can usually be determined, within some constraints, by the tester. Rarely are fewer than 256 sample points used. With current AER instrumentation, 512 or even 1024 sample points are typically used. The intervals between sample points are the same throughout the waveform. The more sample points used, however, the shorter the time interval between any two points. For a given time analysis period, for example 10 ms, sampling 256 points would produce a time interval, or time resolution limit, of about 0.04 ms. The time interval between sample points would be one-half this amount (0.02 ms) for twice as many sample points (512). A practical question, then, is how often does the waveform need to be sampled? With too few sample points (a low sampling rate), valuable information might be lost, especially in determining the precise latency and amplitude of peaks. One guideline for answering the question is the Nyquist theorem: The sampling rate (or frequency) must be at least twice the highest-frequency within the signal spectrum. Another convention is to sample at a rate at least 2.5 times the low-pass cutoff frequency (high-frequency limit of the band-pass filter in AER measurement). This is a simple calculation. If the filter is set at 30 to 3000 Hz, the sampling rate should be 3000 × 2.5 = 7500/sec. If there are 256 sample points in 10 ms, then there are 25,600 sample points in 1 second, a value that exceeds the calculated minimum sampling rate. One clinical implication here is for that longer latency AERs, which are composed of lower frequency energy and recorded with lower band-pass filter settings, the sampling rate is much slower. Information in the waveform will be preserved even with relatively large intervals among the samples.

The measured voltage of the AER waveform is theoretically the same at any instant in time in reality in any one of the time "bins" sampled during the analysis period. During a summing (adding) process, the voltage will get larger. During an averaging process, a response is summed and then periodically divided by the number of stimuli presented. During this process, response will remain at an equivalent voltage. Nonresponse activity, randomly occurring electrical potentials arising from the patient or elsewhere, will not be linked to the stimulus. Within the same time bin just described, therefore, the background noise will have a different voltage for each stimulus. For some sweeps (stimulus presentations), voltage in this time bin will be positive, for others negative. Summing these random positive plus negative values gradually reduces the background activity voltage toward zero. A simple example helps to clarify this concept. A constant waveform (e.g., for an AER) can be thought of as a sequence of voltages (numbers) that may differ across the time period of analysis, but are all the same for a specific time sampled. Averaging a constant number in a time bin, such as three, will always yield this number. If in this time bin, EEG voltages are different for each sweep (random or evenly distributed across many sweeps), the average will approximate zero, just as the average of positive and negative sign numbers (e.g., +3, –1, –3, +2, etc.) when averaged result in zero. EEG noise is best described as a variable distributed randomly around a mean of zero. Standard deviation of the noise is approximately one-half the maximum amplitude from peak to peak. The basic concept in understanding signal averaging is the signal-to-noise ratio (SNR). The overall objective in any AER assessment is to detect a signal (the AER) in activity and the other patient and nonpatient sources of activity. The neural signal (AER) is usually closely time locked to the stimulus. In general terms, that is, if a repetitive stimulus is presented to the patient (same type, intensity, polarity and so on), each component of the response will occur at exactly the same time interval (latency) after the stimulus, while the random noise in which the signal is embedded will systematically cancel out. The signal-averaging computer

within an evoked response system is triggered or initiated at the instant each stimulus is presented. A timing pulse ("sync pulse") sent from the signal-generator to the signal averaging unit of the system assures synchronization of the averaging process with stimulus presentation.

IMPROVING THE SIGNAL-TO-NOISE RATIO (SNR). | There are four major points to remember in clinical AER measurement for optimally applying signal averaging. The first is the mathematical relationship that describes how the AER is enhanced and noise is reduced during averaging. The SNR changes with averaging according to the following equation:

$$\text{SNR} = \frac{\text{S = signal amplitude}}{\text{NR = noise amplitude}} \times \sqrt{\text{N}}\ \text{averages}$$

where SNR = signal-to-noise ratio, and N = noise.

As this equation indicates, there are three ways that the SNR can be increased (improved). Amplitude of the signal (AER) can increase, amplitude of the noise can decrease, or averaging can be increased (a greater number of sweeps). Each of these possibilities will be discussed separately below, but in reality the three usually interact clinically, and an overall objective in optimizing the measurement of AERs is to positively influence all three. Because the increase in SNR is related to the square root of the amplitude of the noise, considerable increments in the number of stimulus presented (and the responses averaged) beyond 1,000 to 2,000 yield diminished returns. That is, improvement of the SNR is much greater over the initial 1,000 (from the start of averaging to 1,000) than for the third increment of 1,000 sweeps (from 2,000 to 3,000). This does not imply, however, that averaging in ABR recording should never continue beyond 1,000 or 2,000 sweeps. The decision to stop the averaging process should not be based on an arbitrary or conventional number of sweeps but, rather, on a clinical or a statistical estimate of the adequacy of the response. Relatively few sweeps (e.g., 200) are quite adequate to produce a well-formed and reliable response. On the other hand, under noisy conditions, particularly near threshold where the response amplitude is smaller, more than 4,000 sweeps may be needed to detect a response. In short, the clinical principle governing the necessary number of sweeps is not intransitive. Averaging can be stopped as soon as a response can be confidently identified above the noise level. If a response is not apparent after the customary number of sweeps are completed, then averaging should be continued until there is little doubt that no response is present. Latency values do not differ for responses averaged for various numbers of sweeps, although latency variability from one averaged waveform to the next is reduced for larger numbers of sweeps. If AER recording involves a summation process, amplitude will progressively increase with additional sweeps and there will, therefore, be substantial difference in amplitude for 250 versus 2,000 sweeps. The averaged AER shows less actual amplitude variation for few versus many sweeps, because of the averaging process, but amplitude will increase as background noise decreases. Initially, it may appear that the response amplitude is decreasing with additional averaging. This is, in fact, because noise contribution in the amplitude of the response is progressively reduced. In summary, then, the SNR increases as a function of N sweeps, but it is heavily dependent the level of background noise and the strength of the response.

Another point is simply an appreciation of the amplitude (magnitude or size) of the signal (the AER of interest). For ABR measurement, the optimal signal amplitude (of wave V) is usually 0.5 μvolts, and the filtered background EEG amplitude is about 10 μvolts, so that 1,600 sweeps are required to achieve a SNR of 2:1. The ALR recorded from a waking patient, in comparison, is on the order of 10 μvolts, while background EEG, filtered considerably less because the response is in the same frequency region, is about 40 μvolts. Only around 64 sweeps are necessary to reach the same SNR level (2:1) since the signal is relatively larger relative to the noise. Less averaging is required to confidently identify larger amplitude AERs. The AMLR Pa component normally has approximately twice the amplitude of ABR wave V. As a result, the signal-to-noise ratio is usually greater, and less averaging is required to obtain a clear and easily identifiable response. A total of 1,000 stimulus presentations is typically adequate, and under ideal measurement conditions (i.e., high stimulus intensity level, quiet but awake normal hearing subject) 512 sweeps or less produces a suitable waveform (Goldstein, Rodman & Karlovich, 1972; McFarland, Vivion, Wolf, & Goldstein, 1975). With appropriate adjustments in filter setting (e.g., opening up the low-pass filter cutoff to at least 1500 Hz), stimulus rate (no faster than about 7.1/sec), electrode placements, and analysis time, and the number of sample points, it is possible to obtain ECochG, ABR, and AMLR information simultaneously from the same waveform (Özdamar & Kraus, 1983; Scherg, 1982a). Also amplitude is directly related to stimulus intensity and usually less averaging is needed to produce a response for high versus low stimulus intensity levels. Amplitude is related to other factors, such as age and gender. More averaging may be needed in infants to acheive a given level of confident response identification because amplitude tends to be smaller than in adults. Since females have larger amplitude responses (at least ABR wave V) than males, less averaging would, theoretically, be required to reach an adequate response.

Finally, amplitude of the noise is an important factor. Reducing the overall amplitude of background noise in AER recording is the most effective means of enhancing the SNR. Limiting noise increases the efficiency and accuracy of clinical AER recordings more than simply averaging additional sweeps. A clinician can often effectively reduce noise from varied sources. Residual noise in an AER recording can be estimated in different ways. A final point, which is recognized but perhaps not fully appreciated clinically, is the

possibility that AERs may not always be closely time-locked to the stimulus and, conversely, that background noise may sometimes not be stationary, normally distributed, or random and may include frequencies (i.e., rate of repetition) that are quite close to the stimulus presentation rate. Maximum SNR improvement in signal averaging occurs when AERs are perfectly related to stimuli and when noise is totally random. This is rarely the case. Slight latency variations in AERs for successive stimuli are normally expected and even greater desynchronization of responses can be characteristic some CNS pathology. Latency "jitter" may even be related to the stimulus. For example, slightly shorter ABR latency for rarefaction versus condensation stimuli introduces increased variability in the responses to alternating stimuli. Inconsistencies in measurement parameters during averaging can likewise contribute to response latency variability. An example would be changes in stimulus intensity resulting from the dubious practice of hand holding earphones. Also, noise encountered in AER recording is not always random but, rather, may occur regularly at a certain frequency (a certain number of times per second). As a consequence, complex interactions among stimulus rate, electrical noise, and AERs are not uncommon clinically. Probably the most well-appreciated problem is due to 60 Hz power line interference. This is sometimes referred to as 60 Hz (or cycle) hum, because if this electrical energy is converted or transduced to acoustic energy, it has a humming sound. If stimulus presentation rate is an even submultiple of 60 Hz (e.g., 10/second or 20/second), that is, can be evenly divided into 60, it is likely that some of the stimuli will be presented in phase (at the same time) that the 60 Hz noise appears in the response. Electrical interference at 60 Hz or harmonics of 60 Hz may be detected with the electrodes or even at one of the unshielded junctions of electrodes or electrode cables between the patient and the amplifier. Since some of the even number of stimuli are periodically time-locked with the electrical interference, the response during averaging appears to undulate, at times being dominated by the interference and then soon after appearing more like the desired response. Additional signal averaging is needed to reduce (but not eliminate) the effects of a 60 Hz artifact. A partial solution to the problem of interference by 60 Hz electrical activity is the routine use of odd stimulus rates (e.g., 21.1/second or 27.3/second) that are not evenly divided into 60 or harmonics (multiples) of this frequency. A simple demonstration of the effect, or presence, of interference at 60 Hz is to average EEG (just as if an AER were being recorded) without a stimulus (e.g., unplug the earphone cable) but with the stimulus rate set at 60 Hz. If interference at 60 Hz is a factor in AER measurement at the test session, it will be readily apparent.

STATISTICAL BASES FOR DETERMINING ADEQUACY OF AVERAGING. | It has been recognized for many years that statistical criteria can be applied in determination of response presence or absence. The criteria are established beforehand and offer the advantage of consistency and efficiency in response analysis. That is, if there is, based on statistical evaluation of AER data, a likelihood of 99.8 percent that a response is present, regardless of the number of sweeps, averaging can be terminated. On the other hand, if after a predesignated upper limit for number of sweeps (e.g., 12,000) this statistical criterion is still not met, averaging stops, and it is concluded that there is no response. Now, selected evoked response systems have the capacity for periodically subjecting AER waveforms to statistical treatment during the averaging process, to automatically and precisely determine when a sufficient number of stimuli have been presented and averaging can stop. Instrumentation for recording the auditory steady state response (ASSR) relies on automated detection of the auditory evoked response, as described in Chapter 8. However, it is still quite common with most AER measurements for the clinician to base the decision to stop averaging on visual analysis of the averaged AER in the context of background noise.

WEIGHTED AVERAGING. | Conventional AEP recording requires the patient to be very quiet, i.e., lying down, relaxed, asleep, or even sedated, because muscular activity produces significant artifacts (EMG) in the frequency range of 50 to 500 Hz, i.e., well within ABR and ASSR frequencies. Their amplitude may be in excess of 100 μV RMS. For comparison, ABR amplitude is in the range of 0.1 to 1 μV and ASSR in the range of 10 to 50 nV. One technique for reducing the effects of EMG artifacts on ABR recordings is weighted averaging. Using this technique, recording periods that contain more artifactual noise are weighted less in the overall average than periods of relative quiet.

In the Integrity™ system from Vivosonic Inc., the relative weighting of recording periods is optimized based a technique known as Minimum Mean-Square Error filtering, or Kalman filtering (Li, Sokolov, & Kunov, 2001; Maybeck, 1979; Sokolov, Zhang, & Long, 2005). The technique estimates the error in each measurement based on the measurement variance and continuously updates this estimate. Using this information, the Kalman filter produces an estimate of the AER signal—for example, ABR—in which the probability of error in the amplitude estimate at each latency point is minimized. By reducing the effects of intermittent EMG noise, the Kalman filtering technique allows ABR to be recorded accurately during substantial muscular activity of the patient—for example, while the patient is moving, eating, sucking a bottle, or talking—despite strong EMG artifacts that may be in excess of 100 μV RMS. Clinically, this means that any of the aforementioned patient muscular activity will not force the clinician to cancel, postpone, or prematurely terminate the scheduled test.

Sweeps or Number of Stimulus Repetitions

There is no standard or invariably "correct" number of sweeps (stimulus repetitions) in AER measurement. Any AER re-

cording is fundamentally a problem of detecting a signal (the AER) in the presence of noise (EEG and measurement artifact). The overall goal is to achieve an adequate signal-to-noise ratio (SNR), where the auditory evoked response is the signal and any other activity detected by the electrodes is the noise. When there is a larger signal and/or less noise, fewer sweeps (stimulus repetitions) are necessary, and vice versa. For a given level of noise, then, more repetitions will be needed for the typically smaller, short latency responses than for the larger, longer latency responses. Increasing stimulus intensity is perhaps the most important technique for increasing the size of the signal clinically, while adequate relaxation is most effective in minimizing noise. Under ideal test conditions, such as measurement of large amplitude promontory-recorded ECochG AP component under general anesthesia, only a handful of repetitions, or even just a single stimulus presentation, is required. A clear, well-formed ABR, and perhaps more often longer latency AERs, appears with one or two hundred sweeps at a high intensity level. Continuing the signal averaging process beyond the point at which a clear response is observed wastes precious clinical time. On the other hand, under poor measurement conditions or to accurately define AER threshold, it may be wise to continue the averaging process well beyond 1,000 to 2,000 repetitions to permit confident identification of a response or to conclude that there is no response.

TABLE 3.4. Questions to Consider Prior to or During AER Measurement

- What is the main objective of testing (see discussion earlier)? For example, is it to rule out a hearing impairment that could interfere with speech and language acquisition, to rule out retrocochlear dysfunction, or to evaluate brainstem or cerebral auditory function?
- What AER information is essential, and what approach will be used for evaluating this information? For example, minimally, the objective may be a replicable ABR wave V at 30 dB to rule out serious deficit in auditory sensitivity or replicable ABR waves I, II, III, and V to describe eighth nerve and brainstem status.
- What information is optimal? If testing proceeds as planned, with a quiet patient and no equipment problems, how will test time be spent and when will testing be terminated? With pediatric ABR assessment, this might involve a full latency intensity function, use of tone-burst stimuli, and, after ABR recording, tympanometry and acoustic reflex measurements bilaterally.
- Will more than one AER (e.g., ECochG, ABR, AMLR, ALR, and/or P300) be assessed, and, if so, what sequence will be followed?
- For a given AER, which specific test sequence will be followed? For example, which ear will be stimulated first, will test ears be alternated, or will data for all stimulus conditions be gathered first for one ear and then for the other ear?

RECORDING AERS

Test Strategies

The first logical step in developing an AER test strategy is to determine why testing is planned. This point was raised in the discussion of preparation at the outset of the chapter. Often the reason for testing is obvious or well known to the clinician. For example, if a clinician's attempts to assess the hearing of infants and young children with behavioral audiometry are unsuccessful and if an ABR is scheduled, the main objective of testing is to estimate auditory sensitivity. And if an adult patient presents with unilateral sensorineural hearing impairment and, perhaps, other unilateral audiologic or otologic signs and symptoms, the reason for AERs is likely to be neurodiagnostic assessment for cochlear versus retrocochlear pathology. Likewise, the rationale for certain applications of AERs, such as newborn auditory screening with ABR, are well defined in advance. The exact reason for others may not be as clear-cut. Reasonable questions to ask before or during an AER assessment are listed in Table 3.4.

There are various ways of verifying the major reason for an impending AER assessment, many of them founded on common sense. Four simple approaches are to (1) review the patient's medical chart or records for tentative diagnoses or impressions; (2) ask the referring health care professional; (3) ask the patient, or the patient's guardian or caregiver, or, if the reason(s) for testing are still unclear; (4) develop a comprehensive and adaptive test strategy based on observation of the patient and the customary reasons for AERs given by the person who referred the patient. That is, in carrying out the evaluation the clinician covers all logical bases and alters strategy in an ongoing fashion as information becomes available. Whenever possible, the clinician should be prepared to answer the question, Why is this patient being tested? Failure to appreciate the reason for conducting an AER assessment at the outset is one of the most common mistakes made by beginning clinicians and a important cause for unsuccessful AER application.

AER measurement in a clinical setting, with varied types of patients and test conditions, is far more challenging, and often frustrating, than data collection from young adult normal-hearing subjects in a laboratory setting under optimal test conditions. It is simply impossible to anticipate or describe each of the myriad test factors that may occur in AER measurement, even though proper clinical decisions in response to these factors contribute importantly to consistently successful AER measurement. Nonetheless, the clinician, especially the beginner, would probably benefit from some guidelines and suggestions on AER test strategy. What follows here, then, is a summary of typical approaches to different types of AER assessments. The author fully acknowledges the limitations of such a "cookbook" format for AER

measurement guidelines. The inexperienced clinician following these step-by-step instructions can, perhaps, be compared to someone inexperienced in cooking who is following a recipe for the first time. With each example, the result may be adequate, but only simple recipes should be attempted at first, and even then mistakes are likely to be made. Consistently good results in recording various types of AERs come only with experience and a healthy dose of creativity. Continuing with this analogy, beginning cooks would be smart to try out their newly developed skills with friendly, sympathetic family members and friends. Similarly, beginning clinicians are advised to first record AERs from understanding normal subjects, rather than diverse types of patients with unknown auditory and/or neurologic diagnoses.

Assessment of Peripheral Auditory Function

ESTIMATION OF AUDITORY SENSITIVITY. | For estimation of auditory sensitivity in infants and young children, the AER techniques of choice are ABR and/or ASSR. The overall objective for the ABR is to determine the minimal intensity level at which a wave V can be reliably observed for each ear. An example would be hearing sensitivity in the speech spectrum region with frequency specific tone burst signals in a very young or a difficult-to-test (e.g., mentally retarded) child. For children with peripheral hearing loss, especially hearing loss in the range from moderate to profound, the ASSR offers distinct clinical advantages. For threshold estimation in malingering patients, recording the ASSR, or the AMLR with tone burst stimuli (500, 1000, 2000, and 4000 Hz), may be more precise and less time consuming.

DESCRIPTION OF COCHLEAR FUNCTION. | ECochG is the AER technique of choice for describing cochlear status and functioning. The overall objective is confident identification of SP and AP components. An example of clinical application is diagnosis of Ménière's disease. ECochG measurement strategies and clinical applications are summarized in Chapters 4 and 5.

DIFFERENTIATION OF COCHLEAR VERSUS EIGHTH NERVE DYSFUNCTION. | The AER technique of choice is combined a ECochG and ABR strategy. Otoacoustic emissions (OAE), of course, are also an important component of the diagnostic test battery. The overall objective is the confident identification of the ECochG AP component (ABR wave I) and ABR waves II, III, and V, even for patients with serious and asymmetric hearing sensitivity deficit. Two examples of clinical applications are the diagnosis of auditory neuropathy and the early identification of eighth cranial nerve dysfunction, e.g., an acoustic tumor.

Assessment of Auditory CNS Function

ASSESSMENT OF BRAINSTEM FUNCTION. | The AER technique of choice for evaluation of brainstem integrity is the ABR. The overall objective is confident identification of wave I, wave II, wave III, and wave V. For patients with serious hearing sensitivity deficit, one can follow the recording guidelines outlined above for differentiation of cochlear versus eighth nerve dysfunction. An example of a clinical application is confirmation of multiple sclerosis or a brainstem tumor.

MEASUREMENT OF THALAMIC AND CEREBRAL FUNCTION. | The AER techniques of choice are AMLR, ALR, P300, and computed evoked response topography if available. The overall objective is confident identification of the AMLR wave Pa for hemispheric and midline electrode arrays (for monaural stimuli), waves N1 and P2 of ALR, and the P300 wave complexes (for binaural stimuli). An example of a clinical application is identification of auditory processing disorder in a child or trauma-related cortical dysfunction.

Components of Efficient AER Assessment

Next to accuracy, speed is the most important ingredient in consistently successful clinical AER assessment. At the very least, prompt collection of necessary data contributes to patient comfort and satisfaction and a more efficient and profitable clinical operation. More importantly, however, speed is often essential in order to collect necessary data. This is especially true in the OR or ICU setting where only timely information is of value. AER findings are reported continuously in the OR, and immediately after testing in the ICU. In essence, old news is no news when decisions on patient management are being made on a minute-to-minute basis. With some pediatric evaluations, recording AERs quickly is almost as important and equally challenging. Usually, children remain sedated or sleeping naturally only for a short period. Furthermore, once awake, they are not likely to fall asleep again. The wisest approach to AER evaluations in these cases is to always collect top priority data, understanding that the child could wake up at any moment. The surest way for a clinician to develop speed in testing is to practice technique extensively with normal subjects prior to gathering clinical experience, but organization and discipline are also necessary. The following specific factors can contribute to more efficient use of test time for the beginner and experienced tester alike.

PREPARATION. | By definition, preparation should be complete before the AER assessment begins. That is, before a patient enters the test room or, for hospital settings, before the clinician arrives at the patient's bedside. Any preparation for an AER assessment after this point is a waste of both patient and clinician time. Preparation is largely a matter of planning and common sense, as demonstrated by the checklist for routine AER assessment displayed in Table 3.5.

PLANNING AND THINKING AHEAD. | Planning, like preparation, is to a large extent a matter of common sense and

TABLE 3.5. Checklist for Steps in Preparation before Auditory Evoked Response Measurement

General

- Adequate supplies are in the test area, including computer disks, data record worksheets, pens and pencils, abrasive liquid, gauze pads, conducting paste and gel, tape, tubephone insert cushions, TIPtrodes.
- Electrodes (including several extra electrodes), electrode box/strip, located near patient head in test area. Disposable electrodes are an option.
- Transducers (earphones, bone vibrator) are near the patient's head in test area.
- Patient area is clean and ready, clean linen is on the bed, a chair for the tester is in place. Residue from previous testing is removed.
- Space is available in the test room for gurney or stretcher if indicated.
- Sterile electrodes are available if necessary.
- Pieces of tape (for securing electrodes) are in a handy location.
- Evoked response equipment has been turned on with current date/time entered.
- Printer is turned on and loaded with paper.
- Initial test program is loaded, or AER measurement parameters are set.
- Patient biographical data is entered into evoked response system.
- Adequate disk space is assured.
- Proper stimulus and stimulus intensity has been verified with a listening check.
- Equipment is ready for electrode impedance check.
- Audiogram, patient medical chart, and other pertinent information is near the evoked response system.

Pediatric

- Chair is available for parent, guardian, or caregiver.
- Indirect, incandescent (not fluorescent), soft lighting is available.
- Pediatric tubephone (foam insert) cushions or electrodes are available if needed.
- Sedation order is obtained, if required, with the proper dose drawn and in the medication in an appropriate dispenser (e.g., syringe, cup), and the nurse or other appropriate medical personnel is at test site.
- Moist face cloth, towel, or paper towel is handy in case patient rejects sedation or vomits.
- A cup of water is handy as "chaser" after sedation, if indicated.
- A stethoscope is handy for assessing vital signs.
- Emergency ("crash") cart handy in case of serious sedation-related complication.
- Patient chart is available for documenting sedation and vital signs.
- Referring physician's name and phone number are available in case of questions or sedation-related problems.
- Immittance and otoacoustic emissions instruments are nearby for measurement of tympanometry, acoustic reflexes, and OAEs as indicated.

concentration on the task at hand. The clinician should have in mind a plan for the ideal test sequence, but also consider contingency plans in the not unlikely event that problems develop. Following a game plan is relatively straightforward when business is as usual. Experienced and well-prepared clinicians, however, are able to quickly adapt new strategies when things do not go as planned. It is advisable to always have a plan for what information one wants to obtain from the optimal AER evaluation—that is, the best case scenario—and also minimal information that one needs to obtain—i.e., the worst case scenario. Realistically, with some patients, especially with young children, it may be impossible to even begin testing. This problem, which is usually related to inability to sedate or an inadequate amount of sedation, is explored further in Chapter 8. The list of dos and don'ts in Table 3.6 is by no means presented as the best or only correct approach for AER evaluation. Rather, it consists of suggestions or guidelines directed mostly to beginning clinicians. Test protocols and procedures for specific AERs are described in subsequent chapters.

DATA RECORD KEEPING AND ONLINE ANALYSIS. | To utilize time most effectively, and to assure that replicable high quality data are acquired, it is extremely important for the clinician to consistently keep records and perform online data analysis during AER assessment. The record keeping is a matter of documenting what has been done, what is being done, and, usually, what is planned. Naturally, in clinical AER assessments, particularly with children or other difficult-to-test patients, plans are subject to change with little or no warning. Many software-based evoked response systems automatically document numerous measurement parameters (e.g., stimulus ear, intensity, rate, polarity, filter settings, number of sweeps and artifacts rejected, electrode montage, and so forth). In the author's experience, however, manually recording essential information about ongoing AER measurement for quick reference is often invaluable in many cases. This functions as a hardcopy backup to the information stored in the computer. It is vital for meaningful data analysis after testing for details such as patient biographical data, test date, or other important information to be entered

TABLE 3.6. Some Dos and Don'ts of Clinical AER Measurement for the Beginner

Do:

- Verify that you are very familiar with the operation of the evoked response equipment and the location of all necessary peripheral devices (e.g., earphones, bone oscillator, electrodes) and supplies (e.g., abrasive liquid, conducting paste, tape, printer paper, etc.).
- Write down important patient biographical data (including medical record number, sedative, and vital body signs), if appropriate, and AER information, in addition to entering it into the evoked response computer.
- Always replicate waveforms, unless a clear-cut criterion for a response is met with a single waveform or well-formed waveforms are apparent in a latency-intensity function.
- Whenever possible, continuously collect (average) AER data during a test session with as little wasted time between the end of one averaging period and the beginning of the next. Plan each step of the test in advance, rather than between periods of averaging.
- Always store all data as soon as possible, even if you're not sure it's important at the time of collection.
- Analyze important evoked response data, at least in a preliminary fashion, to assure validity and completeness before the patient is disconnected and released.
- Keep the patient awake whenever possible for AMLR, ALR, and P300 recordings, yet encourage sleep for ECochG and ABR measurement.
- Plot latency data on latency-amplitude function as it is collected in ABR measurement for estimation of auditory sensitivity and verification of wave V.
- Remove electrodes and earphones (or stimulating electrodes for ENOG) as soon as AER measurement is definitely completed (the validity of data has been verified).
- Get in the habit of analyzing AER results during (NOT after) recording whenever possible.
- Whenever possible, print waveforms during (NOT after) testing.
- Prepare report immediately after testing, NOT later in the day or on another day, whenever possible.
- Periodically monitor vital signs of sedated children.
- Immediately troubleshoot equipment, especially interelectrode impedance and earphone placement if the auditory evoked response deteriorates or disappears.

Don't:

- Erase AER data during collection, unless it is clearly substandard or pure artifact.
- Never simply "eyeball" AER latency or amplitude data to determine the presence or normality of a response. Calculate absolute and interwave latencies (in ms) and amplitudes (in μvolt) before making decisions on further testing or completion of testing.
- Never wake a sleeping infant before first reviewing and verifying with preliminary analysis that all the important AER data are collected and interpretable.
- Remove electrodes and earphones before assuring replicable waveforms and adequacy of data.
- Waste time recording, plotting, or discussing AER data without simultaneously collecting new data (e.g., don't sit in "neutral"), unless absolutely necessary.
- Leave electrodes or earphones on patient after recording is completed and the quality and validity of AER data has been been verified.
- Discuss, interpret, or comment indiscreetly on patient findings in his or her presence during testing. Always remain in strict compliance with HIPAA policies regarding PHI (patient health information). Joking and laughing during testing is likewise inappropriate and unprofessional.
- Have food or drink anywhere on or near an evoked response system.
- Leave a patient unattended for extended periods in test area; never leave an infant or small child alone.
- Turn power for the evoked response system off or on with electrodes on the patient and connected to the system. Always first unplug electrodes from the preamplifier box or strip, or disconnect the electrode cable from the evoked response device.
- Attempt to use AER system, or new or updated AER software, for the first time with a patient. Practice with the device first.
- Use nonsterile needle electrodes with a patient.

into the computer. A few notes on events that occur during the assessment can also be extremely useful to the tester or others during offline (after testing) data analysis. Much of the tester's time during a typical AER assessment is spent in viewing data collection (the averaged response development). Of course, this time should be used for analysis of previously collected AER data and to plan the next logical step in the AER assessment. As the test proceeds, insights and ideas regarding the patient often come to mind during this time and, if they are not written down, they may be forgotten. There is no substitute for diligent record keeping in auditory evoked response measurement.

After the Test

After the last AER has been recorded, and a brief review of collected data confirms that no further testing is required, an adult patient can be informed that the testing is completed

and thanked for his or her cooperation. The first order of business is to gently remove the earphones and electrodes, taking care that the patient's hair remains intact. Excess electrode paste can be removed in a number of ways. Alcohol swabs are effective, but in conscious patients may cause a slight stinging or burning sensation and leave the skin very dry. A moist paper towel is adequate, although considerable scrubbing may be required. Clinical experience with infants, older children, and also adults has shown that prepackaged moist cloths (actually designed for use after a child's diaper is changed) are effective in wiping away excess electrode paste, without drying or irritating the skin. These can be conveniently purchased in many grocery or drug stores (baby supplies section). Finally, adult outpatients appreciate access to a mirror and even a sink in order to freshen up before returning to the waiting room or leaving the test area.

Rarely is it necessary to provide to the patient a detailed verbal description or interpretation of the findings. In fact, it is quite appropriate in most cases to simply state that the recordings are stored in the computer and will be analyzed carefully later in the day. Following the analysis of results, a written report will be prepared and sent to the physician or the referral source. The patient is entitled to a copy of the report, upon request. Report writing is discussed below.

This same general approach is appropriate for the parent of a child undergoing AER assessment, with several exceptions. A sedated and sleeping child must be aroused and examined before dismissal (see the discussion on sedation earlier in this chapter and in the next chapter). Also, if there is no question that the AER findings are normal, parents appreciate receiving the news immediately, rather than waiting anxiously for the official report to arrive in the mail. Counseling the parents of a newly identified hearing-impaired child is an extremely important clinical duty. If this counseling is the tester's responsibility in a clinical facility, it must be done with care, compassion, and understanding. There are certain fundamental guidelines to follow. Guidelines on proper counseling techniques are beyond the scope of this discussion.

ELECTRODE CLEANING. | If disposable electrodes are not used, the best time to clean reusable electrodes is immediately after the recording session is finished, the electrode paste is removed from the patient, and the patient has been counseled and dismissed. Disposable electrodes, of course, eliminate this task. Warm water, disinfectant soap, and a toothbrush (or another soft brush) are usually adequate for cleaning disc electrodes, including ear clip types. Electrodes are then dried immediately with a paper towel and placed near the equipment in their customary storage place. Also, immediately following an AER assessment or just before an assessment begins, it's good practice to clean earphones, probe assemblies, electrode cables, and other components of the evoked response system that will come into contact with the patient. Commercially available germicidal disposable cloths (e.g., SaniCloth Plus®) work very well for this purpose. Representatives from the infectious disease prevention office in a medical center will have good recommendations on disinfecting practices that are effective and pose no risk to the patient. There are many ways of storing electrodes, but it is preferable to allow them to dangle freely from a rack, hook, or other hanger on or near the evoked response system. This facilitates thorough drying after cleaning and reduces the chance of tangled cables. Delaying the cleaning task may lead to later inconveniences and wasted time, as well as shorten longevity of the electrodes due to oxidation. Conducting gel and paste is far easier to remove from electrodes when it is still moist. Within 10 to 15 minutes after testing, the paste will dry and harden, making it difficult to remove. Gel does not harden within hours after testing. If the brief time necessary to clean the electrodes is not available immediately after the test, they can be soaked in a container of water (cup, emesis basin, or bowl) and cleaned later. This practice is not advised, however, because a subsequent AER assessment might be delayed while the electrodes are first located and then cleaned.

Manufacturers may recommend using disposable electrodes for all AER measurements. However, when reusable electrodes are used, they must be disinfected after every use. A mild disinfecting detergent can be used in addition to warm water during cleaning, or the electrodes may be soaked in a hospital-approved liquid disinfectant. Long-term soaking, however, will almost certainly limit the life of the electrode. Electrodes, but not their cables, can be placed in boiling water. Disinfecting electrodes and all parts of evoked response equipment making contact with the patient or the tester's hands after patient contact (e.g., earphones, electrode cables) is particularly important following AER assessment of a patient in isolation (for infection). Obviously, disposable electrodes and insert ear cushions (plugs) eliminate these concerns. Potentially reusable probe tips often coupled to adapters and used in pediatric applications of AERs, such as hearing screening or pediatric diagnostic measurement with ABR, are adequately cleaned by soaking overnight in a hospital-approved disinfectant liquid (e.g., Cidex). Sterilization of electrodes is not necessary after routine AER assessment, but it is good clinical practice after contact with a patient in isolation and essential before electrode use in an operating room in which there will be a surgical field. Sterilization of subdermal needle electrodes is always necessary before their repeated use with a patient. Manufacturers recommend sterilization with gas (Eto). Wet or dry autoclave sterilization is also acceptable, but temperatures must not exceed 140 degrees centigrade (284 degrees Fahrenheit). The routine disposal of needle electrodes after a single use is another viable clinical option.

OFFLINE WAVEFORM AND DATA ANALYSIS. | ECochG analysis is described in Chapter 4, whereas ABR waveform analysis is discussed in detail in Chapter 7. Absolute latency and

amplitude are routinely determined for waves I, III, and V, and sometimes waves II and IV as well. Then, relative latency values, interwave latencies (e.g., between waves I and III, waves III and V, and waves I and V), and relative amplitude measures (e.g., the wave V/wave I amplitude ratio) may be calculated either manually (by moving a cursor onto each of the two waves or subtracting the latency of the first wave from the second wave) or automatically by the evoked response system.

For most evoked response systems, time zero in the analysis period is the default onset of the stimulus. Positioning the cursor on the precise moment of stimulus onset (indicated by deviation of data points from baseline at the first portion of the stimulus artifact) should produce a 0 ms latency display. When one cursor is used to mark waves, the latency displayed is actually the time interval between stimulus onset and the wave. A prestimulus baseline period is very useful in ABR measurement, with data points occurring before the stimulus indicated as negative latency values (e.g., –1.5 ms). A prestimulus baseline period that is 10 percent of the total analysis time is suggested. Latency calculations are straightforward when each wave is clearly recorded with a distinct peak. A suitable test protocol can greatly enhance the likelihood of recording a well-formed and reliable ABR waveform. Realistically, however, ABR waveforms have peaks that are not always clear-cut. There may be multiple small peaks superimposed on a larger wave component, or there may be a prominent "shoulder," particularly in the wave IV–V complex, following the peak. There will probably never be a "standard" interlaboratory approach for latency interpretation. However, within a laboratory or facility, there must be consistency in criteria used by those analyzing and interpreting AER waveforms. Details on analysis for each type of AER (e.g., ECochG, ABR, AMLR, ALR, and P300) are discussed in subsequent chapters.

REPORTING RESULTS. | Patient reports are a vital component of the evoked response assessment. Thorough, even flawless, clinical evoked response measurement is perhaps satisfying to the clinician, but of purely academic value unless the results are communicated clearly, accurately, and promptly to the appropriate persons. AER findings usually contribute to patient management. Clinical decisions based, in part, on AERs vary substantially. ECochG outcome may contribute to diagnosis of Ménière's disease and may lead to a specific medical or surgical course of therapy. Early identification of serious hearing impairment in an infant with ABR may prompt aggressive audiologic management and thereby have a profound impact on the child's communication and life in general. Early identification of retrocochlear pathology in an adult with ABR may prompt aggressive neuro-otologic surgical management and contribute to preservation of hearing or, perhaps, preservation of the function of the facial cranial nerve. The application of AERs in neuromonitoring of patients in the OR or ICU may impact on audiologic or neurological outcome, and even survival. The common and essential link throughout each of these examples of AER applications is an accurate, complete, and understandable report of results. The extent of and demand for reports varies considerably from one facility or clinical setting to the next. One must always keep in mind requirements of third-party payers, as well as professional colleagues, in developing a policy for AER reports.

With current software-based evoked response systems, it is usually possible and rather simple to document in a written printout the biographical data and measurement parameters, as recommended by the American EEG Society Committee. The Committee also offers guidelines for a written and signed report interpreting evoked response findings. Components of the report are (1) the object of the testing; (2) a brief summary of clinical history; (3) the type of evoked response(s) recorded; (4) relevant medications the patient was taking either therapeutically or specifically for the test; (5) a description of waveforms, including wave latency and amplitude data; and (6) the clinical importance of evoked response abnormalities ("alterations") whenever possible. The Committee states that copies of recorded waveforms could either be included with the written report, or supplied upon request.

LETTER FORMAT. | Although the report for each patient should describe his or her unique findings, there are certainly some relatively consistent features of all reports. Furthermore, when AER results are unequivocally normal, a "form letter" report approach is appropriate. A form letter approach is not advised if the results are in any way atypical or abnormal. This is not to say that standard features of the report cannot be stored on a computer for retrieval as the framework upon which the rest of the report is built.

OFFLINE WAVEFORM MANIPULATIONS

Optimally, the quality of AER waveforms is improved by altering test parameters or conditions before or during data collection. With this adaptive approach, the clinician first notices that AER waveform quality is less than optimal and responds by altering the customary test protocol in an attempt to improve quality. If this is not possible, or the result is inadequate, waveform quality can sometimes be improved after data collection is complete. Any processing of AER data after it has been collected, and stored on disk, is referred to as *offline* versus *online* processing. Three offline processing or manipulation techniques for AER waveforms often employed with commercially available instrumentation are digitally adding and subtracting, smoothing, and filtering of AER waveforms.

Adding, Subtracting, and Inverting Waveforms

With many clinical evoked response systems, one waveform can be either digitally added or subtracted from another

waveform. These same systems usually feature an option for inverting polarity of a waveform, i.e., turning it upside down. Instructions for such functions that are specific to a piece of equipment are described in the manual supplied by the manufacturer. In effect, the voltage recorded (and stored) at each data point (e.g., 256, 512, 1,024 total data points) in one waveform is either added or subtracted from the corresponding data point in the other waveform. Therefore, two waveforms that are almost identical will appear unchanged when added. Subtracting one from the other produces what appears to be a flat line because the voltage recorded at each data point is essentially subtracted from itself. Actually, multiple waveforms (more than 2), and waveforms from different patients, can be added or subtracted. Adding a series of waveforms from different patients or from the same patient results in a "grand average" for the group. Similarly, reversing polarity of a waveform is accomplished by changing the sign of the voltage at all data points. For example, if the voltage at exactly 5 ms is +0.37 μvolt, with inversion of polarity it becomes –0.37 μvolt. When this process is applied to all data points, the waveform becomes totally inverted. AER peaks that are customarily plotted upward flip downward and vice versa. A clinical application of the inverting feature is cited below in a discussion of mistakes involving electrode placement or usage.

WAVEFORM ADDITION. | When two waveforms recorded with different stimulus polarities (one waveform with rarefaction and one with condensation stimuli) are added, stimulus artifact is reduced or eliminated. This is because the artifact occurs in opposite directions (upward versus downward going) in each of the waveforms. The result of adding voltages at each data point that are opposite in sign (negative in one and positive in the other) is to approximate zero voltage. The same principle holds for any artifact that is of opposite polarity in the two waveforms.

Multiple replicated AER waveforms for certain stimulus and acquisition conditions (e.g., all recorded with click stimuli presented to the same ear, at the same intensity level) when added create a waveform that is actually the result of the combined number of sweeps (stimulus repetitions). That is, if four waveforms averaged from 1,000 stimuli, all are added together, the resulting waveform is based on a total of 4,000 sweeps. Digital addition of waveforms can thus be a powerful technique for enhancing the signal-to-noise ratio. Clinically, it's generally a better use of time, and statistically preferable, to first record two or even more waveforms for a given set of measurement parameters with a relatively modest number of sweeps, assess repeatability, and then add the waveforms together for latency and amplitude calculation, rather than recording a single waveform for the total number of sweeps. Artifact is less likely to contaminate the final outcome. Another advantage of first replicating waveforms and then adding them together is that atypical waveforms (those with an unusually great amount of noise) can be deleted from the grand average (not included in the adding process). With continued averaging over a large number of sweeps, these noisy AER data would of course be included and would serve to contaminate the waveform. Deletion of noisy runs is a simplified version of the highly sophisticated mathematical signal-to-noise enhancement and AER analysis techniques.

WAVEFORM SUBTRACTION. | ABR waveforms recorded simultaneously with an ipsilateral (i) and a contralateral (c) electrode array (Fz-Ai and Fz-Ac) can be used to derive a horizontal electrode array. Briefly, vector theory predicts, and clinical study confirms, that subtraction of the contralateral (Fz-Ac) recording from the ipsilateral (Fz-Ai) recording yields a horizontal (Ac-Ai) waveform. The validity of this technique is easily proved by then subtracting derived horizontal waveform from a waveform actually recorded, simultaneously, with an ear-to-ear electrode array. The result is a flat line, indicating that the two horizontal waveforms (actual and digitally derived) were equivalent. One obvious implication of digital subtraction, therefore, is the availability of AER data for three channels from only two channel recordings. The clinical advantages of a horizontal electrode array include enhanced identification of waves I and wave III. An ABR recorded with an horizontal electrode array is also less susceptible to electrical artifact.

By subtracting a no-stimulus waveform (just background activity) from an AER waveform to an adequate stimulus, it is theoretically possible to produce a waveform lacking much of the nonstimulus, or ongoing, EEG noise that typically characterizes AERs. Spectral analysis of the waveform resulting from the subtraction process confirms a reduction of low-frequency background brain activity. Although appealing, this approach is not routinely applied clinically. One problem is that the two waveforms (no-stimulus versus stimulus) are not stimultaneously recorded and, therefore, arise from somewhat different EEG environments.

SMOOTHING. | Smoothing is a digital process that, as the term implies, removes small irregularities in waveforms and produces a smoother waveform. High-frequency noise (electrical or muscular in origin) causes many tiny spikes that are often superimposed on the major components in an AER waveform. With three-point smoothing, a common method, voltage at an actual data point in the waveform is replaced by the average of voltages for this data point plus the two adjacent data points (one earlier and one later). Actually, smoothing is a moving average that may include more than three nearby data points. Minor AER waveform "wrinkles" are thus "ironed out." A single waveform can be repeatedly smoothed without producing serious latency distortions. When excessive high-frequency artifact interferes with wave component identification, multiple smoothing may be useful. With repeated smoothing, however, amplitude of small wave components may be reduced because in the smoothing

process, actual peaks are treated the same as high-frequency noise peaks. Also, although smoothing improves the appearance of waveforms and ease of latency and amplitude analysis, rarely do wave components become apparent after smoothing that could not be detected beforehand.

FILTERING. | Filtering is an important factor in AER measurement. Offline digital filtering (after data collection) may be useful in enhancing waveform quality, particularly when electrical activity above or below the frequency range of the response is present in the waveform. Large amplitude, slow wave activity (lower frequency activity), evident with a filter setting of 30 to 3000 Hz, may be minimized with digital filtering at 150 to 3000 Hz, which essentially removes this low-frequency component and facilitates identification of an apparent wave V in the waveform. As a rule, however, such filtering should be done as a last resort in AER recording. Filtering may produce undesirable effects on ABR waveforms if the low-frequency energy contributes critical information for the identification of components. Filtering can, therefore, serve to enhance waveforms but it can also deteriorate waveform quality.

AER MEASUREMENT PROBLEMS AND SOLUTIONS

Some factors that may cause problems in AER measurement or interpretation are easily identified, even before the assessment begins. The effect on these factors (e.g., age, gender, body temperature, hearing loss) on AER latency, amplitude, or morphology can then be estimated, and perhaps corrected, before response interpretation. Other measurement problems, such as electrical or muscular artifact, produce characteristic deviations in waveform appearance. There are a finite number of such problems, as reviewed (along with solutions) in subsequent chapters for ECochG (4), ABR (7), AMLR (11), ALR (12), P300 (13), and electroneuronography (15). The specific problem must first be analyzed and identified. Then, once recognized, the source of the problem is sought out and, hopefully, the problem is corrected or eliminated. At the very least, deleterious effects on AER waveform are minimized. In some cases, however, these types of problems cannot be minimized, and they preclude valid AER measurement. A final group of measurement problems may have multiple causes. Some are due to operator errors, others mechanical failure, and still others result from a certain characteristic of the subject. Examples of these latter problems are absence of response components (waves), poor waveform morphology, or even elimination of the entire response.

Troubleshooting is the term used to describe the process of identifying measurement problems, determining their cause, and, whenever possible, finding an adequate and feasible solution. Troubleshooting requires a rational, logical approach to problem solving and is a skill that improves with experience. As a rule, the first time a certain problem is encountered, the clinician may take some time to find a solution or may not be able to solve the problem independently. Troubleshooting in these instances may involve a trial-and-error solution method, or even telephone calls to other more experienced clinicians. The next time this same type of problem interferes with AER measurement, however, the clinician is able to apply prior experiences and to find a timely solution.

Subject Characteristics

The many effects of subject characteristics on ECochG and ABR are reviewed in detail in Chapters 4 and 7. The effect of one or more subject characteristics must be considered whenever the quality of AER recordings is suboptimal, or at least poorer than expected. By keeping in mind a few general principles of subject characteristic effects, the clinician can often promptly determine whether a specific characteristic should be suspected or can be safely ruled out as a cause of poor AER outcome. These generalizations are as follows:

- Age: Young age (in children) affects all AERs except ECochG, whereas advancing (beyond 50 years) primarily affects P300.
- Gender: Male versus female differences are important mostly for ABR.
- Body temperature: Hypo- and hyperthermia (low and high body temperature) exerts the greatest effect on short latency AERs.
- State of arousal: The effect of subject state is greatest on longer latency AERs.
- Muscular artifact: Movement artifact can interfere with any AER recording, but it is prominent with measurement of the AMLR.
- Hearing sensitivity: Hearing loss may influence any AER, but high-frequency hearing deficits especially affect ECochG and ABR recordings.
- Drugs: Drugs that influence the CNS (e.g., sedatives, anesthetic agents) exert the greatest effect on longer latency, cortically generated AERs and have virtually no influence on ECochG and ABR.

Electrical Interference

Since AER measurement involves detection of minute (several μvolts or less) electrical events within the ear, auditory nerve and brain with electrodes typically located on the surface of the scalp, it is not really surprising that electrical interference can be a major problem. Surface electrodes are just as likely to detect extraneous electrical activity outside of the head as stimulus-related activity within the head. In fact, the unwanted extraneous electrical activity may be far more prominent. Fortunately, when each electrode in a pair detects similar electrical artifact, that is, artifact that is of similar amplitude and phase), then it will largely be can-

celled out (rejected) by the differential amplifier. A problem arises, however, if such electrical artifact is detected mostly by just one of the electrodes in the pair.

Another factor contributing to electrical interference in AER recording is the amount of amplification required in processing the responses. Before the electrophysiologic activity of less than a millionth of a volt can be processed and analyzed with an evoked response system, it must be amplified up to 100,000 times. Amplification not only increases the problem with extraneous electrical activity detected by the electrodes, but it also introduces electrical noise to the auditory evoked response waveform from the amplifier circuit. Of course, circuitry for various brands of evoked response systems differs in the amount of noise produced during amplification. Finally, transducers that produce acoustic stimuli necessary to evoke an AER are electromagnetic devices that can, in fact, be a source of electrical artifact. Again, the amount of electrical interference varies among transducer types.

STIMULUS ARTIFACT. | Among electrical interference problems, stimulus artifact is probably the easiest to isolate and solve. This discussion is limited to electrical artifact produced by acoustic stimulus transducers. Artifact problems associated with electrical stimulation used in electrically evoked responses and electroneuronography (ENoG) and are reviewed in Chapter 15. Acoustic transducers (various types of earphones) produce electromagnetic fields. That is, they generate electrical activity. Very often, the acoustic transducer generating the stimulus for an AER is located close to an electrode recording the AER, and stimulus-related artifact would seem to be unavoidable. These undesirable interactions between electrical activity from earphones and recording electrodes can be reduced or eliminated with some common sense precautions.

Early investigators of AERs recommended electromagnetic shielding of earphones with a layer or two of special metals (Coats, 1984; Elberling & Salomon, 1973). The shielding is designed to contain the electromagnetic energy and insulate adjacent electrodes from its effects. Shielding of earphones is expensive, may produce unwanted changes in the acoustic properties of the transducer, and is not really a practical alternative for most clinicians. Shielding also is not an alternative with bone-conduction transducers (oscillators or vibrators).

The best general technique for reducing stimulus artifact is to put as much distance as possible between the transducer (earphone) and cables and the recording electrodes. The tubing for insert electrodes permits this distancing, and the time delay from the transducer (box in the figure) and earplug creates a delay between the stimulus and early components of the ABR (e.g., the AP or wave I component). For any kind of transducer, wires leading to the earphone that carry an electrical signal and aren't completely insulated should be remote from electrode leads. These two types of wires should not make contact or be draped over one another at any point along their course. One simple method of avoiding such contact is to extend electrode leads in one direction (e.g., up toward the top of the head) and the earphone transducers (for inserts) and cables in another direction (e.g., downward toward the chest), or vice versa. Since electrode leads may function somewhat as antennae in picking up unwanted electrical activity (from the air), shorter leads are desirable. Ideally, there would be no distance between the electrode and the amplifier. The typical electrode lead, which is 1 meter (about 3 feet), may be adequate in most settings but specially constructed shorter leads (2 feet or less) are helpful in reducing artifact in especially noisy test environments. Braiding (intertwining) electrode leads also tends to reduce the likelihood of electrical interference. Tracking a specific electrode from one end to the other, for a color-deficient tester, is particularly difficulty when a group of electrodes are braided.

With a conventional supra-aural audiometric earphone (TDH-39 or TDH-49), the earphone is often resting on a mastoid or earlobe electrode. At high intensity levels, stimulus artifact may create a serious problem because stimulus-related waves extend into the time frame of the ABR. There is an additional problem with evoked response instrumentation if an automatic display gain option is selected. The size of waveform displayed on the screen is adjusted on the basis of the largest peaks so that a fixed portion of the screen (e.g., one-third) is filled. If the stimulus artifact is large, the remainder of the waveform (the actual response) may be scaled down excessively, sometimes appearing as a flat line. Some evoked response systems offer a blocking feature in which the display in the time period of the stimulus (around 0 ms) can be eliminated. Display scaling is therefore determined by the actual response waveform, rather than by stimulus artifact. This technique does not, however, actually solve the artifact problem and may actually contribute to other problems with measurement or analysis. The most effective means of reducing stimulus artifact with supra-aural earphones is to rely on alternating polarity stimuli. The artifact produced by each of the two polarities is opposite in direction and when averaged (summed) is mostly cancelled out (the positive plus negative voltages when added approach zero voltage). The obvious limitation of routine use of alternating polarity stimuli is that a single polarity (rarefaction) is preferable in most patients. One way around this dilemma is to first record replicated responses with each polarity (rarefaction and condensation) and then, if excessive stimulus artifact is present, to digitally add waveforms for the two polarities.

Optimally, alternating polarity stimuli are presented, but waveforms are separately averaged in one channel for rarefaction clicks and another channel for condensation clicks. Some evoked response systems have this capacity. The process can also be implemented by adapting the P300 program for some evoked response systems. That is, instead of frequent versus rare tone burst stimuli with a rare stimulus probability of 20 percent (as in P300 measurement), the

condensation and rarefaction clicks are presented with a 50 percent probability. The process of adding and subtracting waveforms was described above. The effect is a set of waveforms essentially produced by alternating stimuli. Stimulus artifact should be minimal. This approach, of course, is not necessarily time effective nor ideal clinically since averaging a response to both polarities doubles test time and might not have been required, and the adding process must be done off-line, precluding ongoing analysis of data.

Perhaps the most effective method for reducing stimulus artifact is use of insert earphones (e.g., Etymōtic Research ER-3A). Electrical activity is generated from the cable leading from the plug to the box and by the box that houses the transducer. Then, an acoustic signal travels down the plastic tube to the insert cushion. The objective, then, is to keep the earphone cable and box as far away from electrode leads as possible. The plastic tube is not a source of electrical activity and will not produce stimulus artifact, even it is resting on an electrode lead. Insert earphones contribute to reduced stimulus artifact in two ways. The transducer (box) can be positioned away from electrode leads. The more the transducer is separated from the electrode, the less likely the artifact. Also, the plastic tube produces a time delay between stimulus and response. As manufactured by Etymōtic, the length of tubing produces a delay of 0.8 or 0.9 ms. Even if stimulus artifact is present, the delay virtually eliminates any interference with identification of early AER components (e.g., ECochG SP or AP components, or ABR wave V). Other advantages of the tubephones (e.g., comfort, less ringing, prevention of collapsing ear canals), and some associated precautions (e.g., accounting for the time delay in absolute latency calculations, lack of an interaural attenuation advantage) were reviewed earlier.

ELECTRICAL NOISE AND ARTIFACT. | Electrical power in the United States is supplied with a frequency of 60 Hz. The power line frequency in Europe is 50 Hz. Any electrical outlet or electrical device may produce electrical noise with a frequency of either 60 Hz or of harmonics of this frequency (e.g., 120 Hz), or much higher frequencies that are not multiples of 60 Hz. Examples of the numerous sources of 60 Hz electrical noise (also referred to as line noise) in a clinical setting include electrical wiring in a test area, fluorescent lights, X-ray viewing boxes, power transformers, copy machines, conveyer belts, escalators, elevators, whirlpools in physical therapy, electrical machinery, patient video monitors, blood pressure transducers, computers, heating blankets and incubators, EKG (electrocardiogram) equipment, and operating room microscopes. Even the evoked response system itself, especially the monitor, can produce excessive electrical artifact in AER measurements if positioned close to the recording electrodes. From this partial list of electrical interference suspects, it is clear that some test settings are inevitably quieter electrically than others. The ideal test environment is a relatively isolated area (none of the devices listed are on a floor above or below, nor in any nearby room), with new preferably dedicated wiring (no other equipment or devices are on the same lines) in which AER recording is done with the patient in a radio-frequency (RF) shielded room. At the other extreme of the electrical noise continuum is the typical newborn or surgical ICU or operating room (OR) that is filled with the above-noted electrical devices (many of them life supporting), has electrical wiring that supplies a variety of machines and functions, and is adjacent to other trouble spots, such as an X-ray department. Electrical interference may be extremely unpredictable, as well as elusive. That is, at one test session there may be so much interference that AER recording is impossible, yet at some other time in the same setting there is electrically silence. Electrical interference may be highly unpredictable. That is, during the course of a 6-minute test session, significant electrical interference may appear and then disappear. Serious electrical artifact may appear in one electrode channel but not in another simultaneously recorded channel and then, inexplicably, the artifact problem may appear in the opposite channel. Although this is an extremely frustrating feature of electrical interference, it does suggest that one possible solution is simply to "wait out the storm."

A rather consistent observation regarding electrical interference and electrode arrays deserves mention at this point. In very noisy environments, considerably less electrical interference is typically found for a horizontal (ear-to-ear) recording array for the ABR than for electrode arrays consisting of one electrode on the forehead or vertex. Typically, waveforms recorded with a forehead noninverting electrode are characterized by excessive high-frequency artifact, although the actual frequency of the artifact is different in each case. Yet the Ac-Ai electrode array often is remarkably clean. As noted above, if the same electrical interference were present at each of the electrodes in these four pairs, it would be minimized by differential amplification (cancelled by subtracting the inverting from the noninverting input). The figures, however, suggest that the electrical interference is different as detected by the forehead (or vertex) electrode versus ear electrodes. With differential amplification, the artifact is therefore not rejected at the amplifier and persists in the Fz-to-ear array. The artifact is apparently common to the two ear electrodes and is largely rejected at the amplifiers. A practical implication of these patterns is that electrical interference in conventional electrode arrays (ipsilateral or contralateral) that precludes meaningful waveform interpretation might be minimized by digital subtraction of the contralateral waveform from the ipsilateral waveform (as described above). This, in effect, subtracts the activity (including interference) at the forehead (or vertex) site from itself, leaving the ear-to-ear electrode array.

There are two fundamental approaches to dealing with 60 Hz, or any other, electrical artifact. The first, and most effective, is to determine and eliminate the source. The other approach, which is often really a last resort, is to attempt to

minimize the effect of the artifact on AER measurement. The following is a general discussion of this topic. Problems encountered more frequently in specific test environments, such as the newborn ICU, OR, or surgical ICU are noted in Chapters 6 and 10. Møller (1987) provides a detailed and highly informative discussion on localizing sources of electrical interference and reducing their effects on evoked response recordings. Although his focus is electrical interference in the operating room, the troubleshooting principles he describes are equally valuable for any test setting. According to Møller (1987), unwanted electrical noise interferes with evoked response equipment and recordings via four pathways: (1) Unshielded electrodes and electrode leads act as antennae in picking up airborne activity from nearby sources, (2) activity may be transmitted to the patient from other electrode leads (not used in evoked response measurement) connected to other electronic devices (e.g., EKG or heart monitors) and then on to the evoked response equipment, (3) evoked response electrodes pass through magnetic fields and conduct magnetic energy on to the evoked response equipment, and (4) power line electrical activity enters the evoked response system amplifiers and appears in waveforms.

Various sources of electrical interference and some techniques for reducing the effects on evoked responses are detailed for ECochG and ABR in Chapters 5 and 7, respectively. Detection of specific sources of unwanted electrical activity in a test area is not always possible, but should be attempted, particularly if the problems are consistently encountered and evoked responses are routinely recorded in the setting. The overall objective in this situation is a systematic and, hopefully, permanent remedy for the electrical interference problems rather than spending time during each test session attempting to circumvent the interference. Møller (1987) provided instructions for constructing simple antenna-type devices for detecting sources of electrical and also magnetic interference. A length of wire (for electrical interference) or a wire loop (for magnetic interference) can be plugged into one input of the differential amplifier (the positive or negative electrode input) for the evoked response system. The other input is grounded. The amplifier output is sent to an oscilloscope or loudspeaker, rather than to the evoked response system. The clinician then places the antennae near suspected sources of electrical interference and notes the presence of electrical activity on the oscilloscope or via the loudspeaker. With this "ghost-busting" technique, it is often possible to pinpoint sources of electrical interference and, sometimes, to determine frequency characteristics of the interference. Knowledge of the electrical activity waveform for different electrical devices might be useful in solving future artifact problems.

The alternative to eliminating the source (s) of electrical interference is to manipulate the test protocol so as to minimize the effect on AER recordings. Manipulation of electrode configuration was noted above. Electrical interference is more likely if the interstimulus interval (the stimulus rate) is even divided into 60 (60 Hz). An odd stimulus rate (e.g., 21.1/sec) reduces the likelihood of an interaction. Electrical interference at 60 Hz may interact with some stimulus rates to produce undulations (waxing and waning) in the appearance of electrical artifact in the waveform. Adjusting the stimulus rate slightly often minimizes the contamination of the waveform by this electrical interference. The extent of electrical artifact may fluctuate also with the number of sweeps. It is sometimes possible to manually stop averaging at a point of relatively waveform clarity. Altering filter settings is usually a futile technique for reducing excessive electrical interference. The use of a notch filter at 60 Hz is rarely helpful because harmonics (higher multiples of 60 Hz) are still passed into the averaging process. As noted above, the frequency of unwanted electrical interference may fall well within the frequency region of the AER being recorded. Furthermore, notch filtering produces undesirable filter ringing and response latency distortion. In short, notch filtering is to be avoided. With electrical interference at 400 Hz, for example, it is impossible to filter out the artifact without eliminating important spectral content of the ABR, ranging from below 100 Hz to over 1000 Hz. Other possible methods of reducing the effects of electrical interference artifact on AER recordings involve manipulation of the test environment rather that test protocol. Simple and routine precautions, such as either braiding a set of electrode leads (wires) or tying the electrode wires into several loose knots, will often minimize or even eliminate some types of electrical interference from averaged auditory evoked response waveforms.

As reviewed earlier in this chapter, conventional AER measurements are made with patient-mounted passive electrodes that are connected to lead wires. The leads are, in turn, electrically coupled to the inverting and noninverting inputs and the ground of a differential preamplifier. The length of each lead wire is typically in excess of 1 m. Electric and magnetic fields from surrounding electrical wiring, and various equipment in the measurement environment, contaminate the AER measurement by inducing electrical currents and generating voltages in the lead wires. The amount of contamination from the electric field increases with the length of the leads, while the amount of contamination from magnetic fields is proportional to the area of the three loops formed by the inverting, noninverting, and ground leads (Ferree, Luu, Russell, & Tucker, 2001). Another significant extraneous source of noise is motion artifact—i.e., the noise induced in lead wires as a result of their movement through a magnetic field (Bell, Smith, Allen, & Lutman, 2004).

An alternative arrangement that reduces the effects of electric and magnetic fields on AER measurements is the Amplitrode™ (Figure 3.16), available as part of Integrity™ system from Vivosonic Inc. The Amplitrode™ integrates an AER preamplifier and clip that snaps directly onto the ground electrode, thus eliminating the ground lead wire completely. Furthermore, since the preamplifier is mounted directly on the patient's head, the inverting and noninverting

FIGURE 3.16. The Amplitrode™ combination electrode and amplifier.
Courtesy of Vivosonic.

signal lead length and corresponding loop areas are minimized, while the leads themselves are electrically shielded (Kurtz & Sokolov, 2005; Metting Van Rijn, Kuiper, Dankers, & Grimbergen, 1996).

ELECTRICAL SAFETY. | Concern for patient safety and comfort should always be foremost in the minds of clinicians carrying out evoked response measurements. Electrical safety is an important consideration in recording AERs, as well as electrically stimulated evoked responses. Isolation transformers contribute to patient safety. As emphasized throughout the book, an evoked response system should never be turned on or off with the patient connected to the device with electrodes. Electrodes should be removed from the electrode box or preamplifier before power is changed to the system.

Measurement Problems and Solutions

Some measurement problems are common to all AERs, and troubleshooting procedures tend to be fairly consistent among AERs. That is, many of the items in a troubleshooting checklist are the same for all AERs. For any of the AERs, selected problems solutions are identical, because basic equipment malfunction or misuse inevitably produces the same constellation of symptoms. At the same time, other problems that appear to be quite similar often differ in the extent with which they affect AERs. For example, profound hearing impairment can account for absence of any AER. Certain anesthetic agents, on the other hand, can account for absence of the AMLR or ALR, but not the ECochG or ABR. Also, stimulus artifact within the first millisecond or two after the stimulus can interfere with ECochG and ABR analysis, but is of no concern with later latency responses. A detailed discussion for specific AERs is offered in subsequent chapters. The symptom-oriented format was chosen because it most closely resembles clinical reality. Because of the common effect of some problems on AERs, there is a certain degree of redundancy in the problems and solutions listed in the series of tables. The beginner is advised to purposefully make as many of these mistakes as possible, in a controlled setting, before venturing into clinical AER measurement. The least threatening way to follow through on this recommendation is for the clinician, with plenty of time and behind closed doors, to prepare him- or herself, or a good friend, for each type of AER. The first objective is to obtain a high-quality normal response. Then, by systematically altering the measurement parameters or purposefully committing technical errors, such as leaving an electrode unplugged, using an inappropriate filter setting, and so forth, the clinician can view firsthand many of the symptoms that are listed in the tables. A "mistake-making session" can also be valuable laboratory assignment in workshop or a graduate level course on AERs.

CLOSING COMMENT

The objective of the foregoing review was to introduce the reader to principles important in recording auditory evoked responses in general. Principles, protocols, and procedures of specific auditory evoked responses are discussed in more detail in subsequent chapters. However, the clinician who understands principles that are common to all AERs will readily learn the techniques and strategies that are essential for recording each specific type of AER and, in all likelihood, auditory evoked responses that are discovered and applied clinically in the future.