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Foreword

Dr. Field Rickards, who was among the earliest investigators of the auditory steady-state response (ASSR), has noted that "periodic potentials" were first recorded from human subjects close to 40 years ago, and that the ASSR has been applied clinically at several centers in Australia and Canada for more than 20 years. However, because devices approved by government agencies for use with patients were lacking until the past decade, particularly in the United States, audiologists tend to view the ASSR as a new technique for auditory assessment. Without doubt, one measure of the acceptance of a clinical technique in audiology is a publication of a book devoted entirely to the technique. Those of us who have been practicing audiology for over 30 years all remember the excitement surrounding publication in 1975 of the *Handbook of Clinical Impedance Audiometry*, edited by James Jerger. Aural immittance (then impedance techniques), subsequently became a regular and invaluable component of the clinical audiology armamentarium. The same clinical phenomenon was repeated 10 years later with the appearance of *The Auditory Brainstem Response*, edited by John Jacobson. Toward the end of the 1990s, two books were published that focused exclusively on otoacoustic emissions—*Otoacoustic Emissions: Clinical Applications*, edited by Martin Robinette and Theodore Glattke, and the *Handbook of Otoacoustic Emissions*, written by James W. Hall III. The books were written, in large part, in response to growing demand by audiologists for more information on this latest addition to the clinical test battery.

Confirming the essential role of the ASSR in the assessment of auditory function, especially in children, *The Auditory Steady-State Response: Generation, Recording, and Clinical Application*, edited by Gary Rance, will now take its place among the collection of thorough treatises on important clinical procedures in audiology. As will be apparent from a perusal of the table of contents, the book includes chapters by many of the best-known names associated with basic and applied research on the ASSR.

Understanding anatomical origins and physiological mechanisms is critical for recording, and maximum clinical exploitation, of any auditory electrophysiological response. Three early chapters of the book are set aside for rather rigorous discussion of the "basic science" and "technical concepts" underlying the ASSR. Of course, despite extensive research efforts, our understanding of the neural origins of the ASSR remains incomplete. The information represented in this book, however, describes what is known at this time. The book next presents a number of chapters on clinical application of the ASSR and topics, such as nonpathologic factors, that must always be considered for meaningful analysis and interpretation of an electrophysiological response. The assignment of entire chapters to

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selected clinical applications of the ASSR —among them estimation of behavioral auditory thresholds for air and bone conduction signals, infant hearing screening, and the use of ASSR in hearing aid fitting —attests to the clinical value of the ASSR, and to the wealth of practical information now available to the audiologist. The book concludes with a chapter containing eight case studies that illustrate various applications of the ASSR and, in addition, serve to reinforce the concepts and technical points noted elsewhere in the book, followed by a look to the future.

With the emergence of any new clinical technique, there is a tendency among audiologists to question the relevance of preexisting procedures, or to pose the unanswerable question of which technique is "better." Some audiologists may even wonder whether, with the availability of ASSR, there is still a role for the auditory brainstem response (ABR) and, especially, frequency-specific (tone-burst) ABR measurement. Within the rather brief history of clinical audiology, it has been repeatedly confirmed that new clinical techniques do not supplant older techniques; rather, new techniques complement the existing techniques. Put simply, the audiologic test battery gets bigger and better. The diagnostic power of the latest auditory electrophysiology technique—in this context, the ASSR—is wholly dependent on its consistent clinical inclusion within a test battery, and on its clinical interpretation with the context or the pattern of other audiologic findings. With the publication of *The Auditory Steady-State Response: Generation, Recording, and Clinical Application*, we have the first comprehensive review of a the clinical technique. I predict that accumulated clinical experience will, in time, reveal additional diagnostic applications of the ASSR in clinical audiology and that the full ASSR story will unfold in later editions of this book.

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CHAPTER 2

Introduction to Technical Principles of Auditory Steady-State Response Testing

M. SASHA JOHN
DAVID W. PURCELL

This chapter is dedicated to enthusiastic audiologists who have helped to push the field of auditory steady-state response testing forward.

Introduction

Auditory steady-state response (ASSR) techniques approximate the goals of objective evoked-response audiometry: No subjective responses are required on the part of the person being tested, and the detection of the evoked responses occurs automatically using statistical methods implemented by the computer. Within such a testing paradigm, what is the role of the well-informed audiologist? Although automation provides the objective detection of ASSRs themselves, audiologists must be responsible for adjusting the protocol as the test progresses and for ensuring that the results make sense. Clinical audiology is, as we know, a mixture of science, art, and experience, and this will likely always be true regardless of the tool being used.

When performing ASSR testing, the audiologist is immediately faced with a number of questions related to technique, results, and their interpretation. Although answers have been obtained for some of these questions, several

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issues are still outstanding in this relatively new and constantly evolving field of steady-state evoked response testing. Furthermore, it is likely that the answer to a particular question may depend on the testing situation, and rules of thumb must be implemented using common sense and experience.

This chapter reviews the fundamental technical concepts that underlie stimulus generation, response detection, and threshold estimation. Several candidate "solutions" to a number of commonly encountered technical problems are presented as well. Some equations are provided to show how certain principles are functionally implemented, but the underlying math is largely sidestepped. Armed with this information, audiologists should feel more comfortable about interpreting the "objective" results that are provided by ASSR software packages and should be able to use the time available for testing in a more efficient and effective manner.

Overview of Auditory Steady-State Response Testing Techniques

This section provides an overview of what occurs during ASSR testing, as illustrated in Figure 2–1, and introduces some key terms and concepts, which are then reviewed in more detail throughout the chapter. The top of the figure depicts the creation of a stimulus, its presentation to a patient's left ear, the processing of the sound in the cochlea and the brain, and the recording of the resulting brain electrical activity as reflected in the electroencephalogram (EEG). The second row depicts the automatic processing of data and statistical evaluation of the response as accomplished by the ASSR software.

In order to obtain frequency-specific estimates of hearing, the ASSR stimuli can be presented sequentially or simultaneously. When multiple tones are tested simultaneously, this may be known as the *multiple auditory steady-state response* (MASTER) technique. Other names for this technique, such as *multiple-frequency ASSR* and *multiple-ASSR*, also are in use. Multiple carrier frequencies (Fc), each having a unique modulation frequency (Fm), can be added together to form a *compound stimulus* for use in testing (labeled "Sound" in the figure). During ASSR testing, this stimulus is converted from its digital representation within the computer's memory (known as the stimulus buffer) into an analog voltage signal, which is then provided to an acoustic transducer and presented as sound to the patient. Converting the stimulus from a digital set of numbers into an actual voltage signal of the sound is known as *digital-to-analog conversion*, whereas recording the EEG and storing it as a series of numbers in the computer's data buffer is termed *analog-to-digital conversion*. When both ears are tested, two stimulus buffers can be used to store the stimuli that will be delivered to the left and right ears.

Owing to the tonotopic representation of the cochlea, each of the one or more modulated carriers will be processed by relatively independent regions of the cochlea (see "Cochlea" in the figure). In each cochlear region, the response will be initiated at the modulation rate of each carrier. From the cochlea, the signals will travel more centrally (see "Brain" in the figure) through the primary auditory nerve (1) to the brainstem (2) and then, when the modulation rate

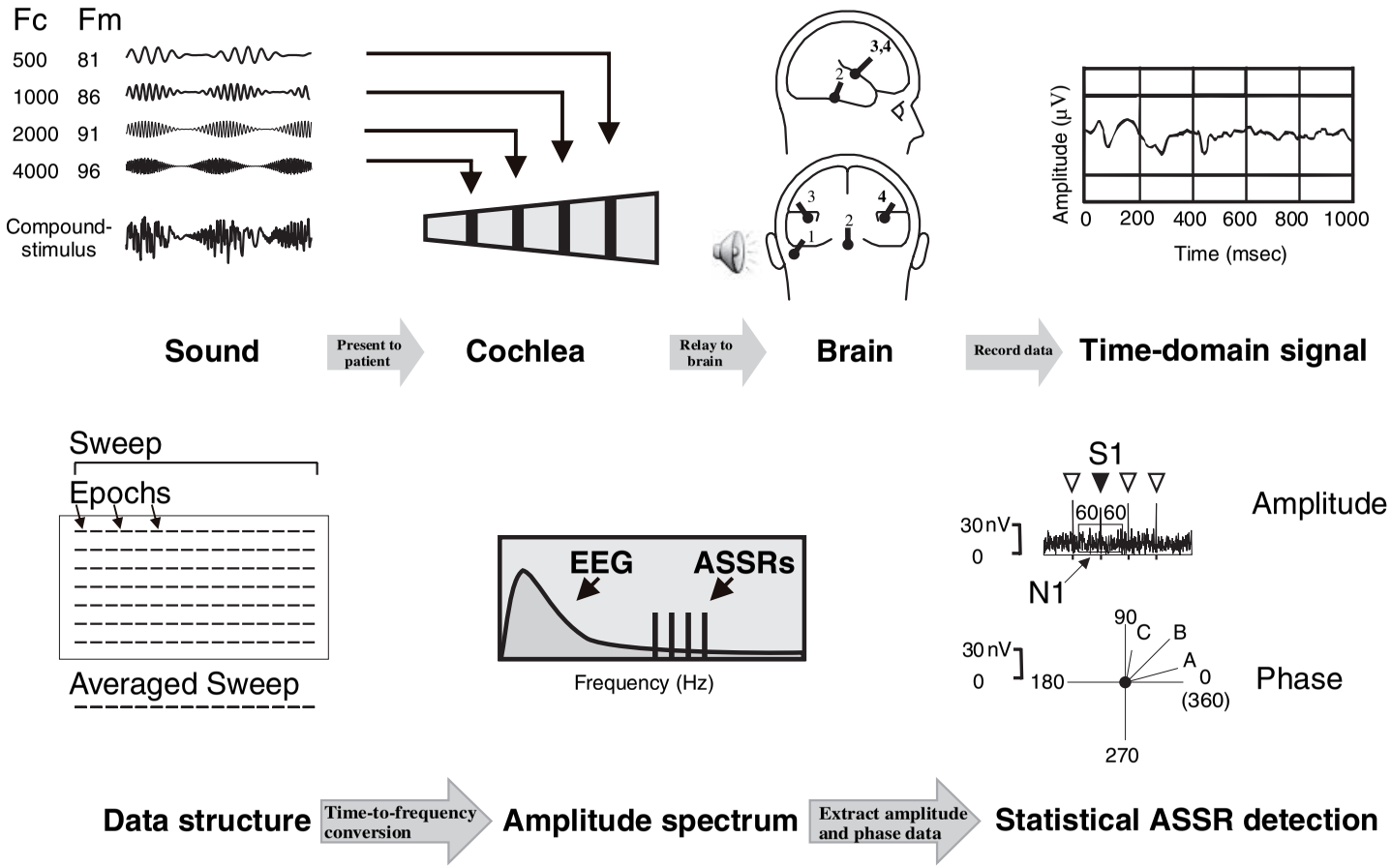

Figure 2–1. Overview of ASSR testing. *Top row* includes creation of auditory stimuli, presentation to the patient, and collection of epochs of EEG (including evoked-response) data. *Bottom row* includes organization of epochs into sweeps residing in a data structure, averaging of the data structure, time-to-frequency conversion of the averaged sweep, and statistical analysis of the resulting amplitude spectra using either amplitude-based or phase-based methods. For additional details, see text.

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is slow enough (e.g., less than 70 Hz), the signal is bilaterally relayed to the ipsilateral and contralateral primary auditory cortex (3 and 4). Because the sources of the ASSR (and the corresponding locations and orientations of the recorded dipoles) can vary as a function of the age of the patient and the modulation rate being used, the optimal locations for placement of electrodes to record the evoked potentials also may vary (Herdman et al., 2002; John et al., 2000; Van der Reijden, Mens, & Snik, 2005).

Using scalp electrodes, the EEG signal can be recorded and then amplified (e.g., increased by a factor of 50,000) as well as filtered (e.g., using a high-pass filter of 10 Hz to remove low-frequency energy and a low-pass filter of 300 Hz to deter aliasing, as will be described), before undergoing analog-to-digital conversion. Once the EEG signal has been digitized into a series of numbers, it can be displayed on a computer screen as a time-series voltage-signal (labeled "Time-domain signal" in the figure). The recorded EEG signal will contain the brain activity evoked by the stimuli (known as *signal*—the ASSR), as well as ongoing brainwave activity that is unrelated to the processing of the sound stimuli (known as *noise*).

The material presented in the remainder of this section gets a little more complicated. It may be beneficial to simply skim it and get a general understanding of the concepts and terms. After reading the remainder of the chapter and returning to this section, this overview should be much easier to digest.

The EEG signal collected during the ASSR testing is stored in the computer's memory in segments known as *epochs*. These epochs can be of any length but normally are about 1 or 2 s in duration. As the recording continues and more epochs are collected into the data structure, these may be linked into larger segments known as *sweeps*. This maneuver serves to increase the length of the data segments that are submitted to the fast Fourier transform (FFT) algorithm, thereby increasing the frequency resolution of the amplitude spectra used to evaluate the ASSR (as described further later in the chapter). Sweeps may last any amount of time, but in Figure 2–1, these last 16 s and form rows of our dataset. Accordingly, a test record that lasts about 2 minutes will result in a dataset (labeled "Data structure" in the figure) with 8 rows; where each row is a 16-s sweep (8×16 s = 128 s), and the columns are the individual 1-s epochs. In order to increase the size of the signal (i.e., ASSRs) relative to the size of the noise (i.e., the unrelated EEG activity), known as the *signal-to-noise ratio* (SNR), the sweeps can be added together in order to obtain an "average" sweep. This is the same logic that underlies collecting a large number of transient responses to click stimuli: Components such as wave V are time-locked to the click-stimulus; unrelated background activity is not, so the latter type of energy averages toward zero as more responses are collected.

The averaged sweep can then be converted from the time domain into the frequency domain to produce a *spectrum* (often only the "amplitude spectrum" is shown), which provides an estimate of all of the different frequencies present in the averaged sweep. The ASSRs will show up as peaks in the amplitude spectrum at the frequencies at which the auditory steady-state stimuli were modulated (see "Amplitude spectrum" in the figure).

The final portion of Figure 2–1 illustrates that ASSRs can be detected using statistics that evaluate either the ampli-

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tude or the phase of the ASSRs. Amplitude-based statistics, such as the F-test, will evaluate if the energy of a particular ASSR (labeled S1 in the figure) is statistically of greater amplitude than that of a background noise estimate (calculated as the average energy within the box labeled N1). The amplitudes of the signal and noise are compared as a ratio, known as the *F-ratio*, which is evaluated using 2 (numerator) and 2*n* (denominator) degrees of freedom, where *n* is the number of noise frequencies that were used to create the noise estimate (i.e., the width of the box N1). With use of 120 frequencies as the noise estimate (60 above, and 60 below, the ASSR frequency), the F-ratio that must be exceeded to detect a signal at the $p < .05$ level is 1.75 (i.e., the amplitude of the signal must be 1.75 times as big as the amplitude of the noise to be statistically detected).[1] Generally, as more frequencies are used to create the noise estimate, the estimate becomes more stable, and therefore the criterion that must be met for the F-ratio to reach significance is decreased.[2]

Phase-based statistics are used to detect ASSRs by evaluating the "phases" of the responses to see if these are nonrandomly distributed. As shown later on, ASSR phases are related to the time interval between when a portion of the modulated stimulus was presented and when that same portion was processed by the brain (as evidenced by an evoked response). The assumption is that if the auditory system is "locking" to the modulations of the auditory stimulus, then the sets of evoked responses will occur at similar times (i.e., the phases will be similar).

ASSR data often are displayed in polar plots (see Figure 2–1, bottom row, right). A *polar plot* is a two-dimensional coordinate system in which each ASSR can be plotted as a point determined according to its phase and amplitude. The two axes define all angles between 0 and 360 degrees (i.e., throughout a full circle), and as one moves counterclockwise, the phase values increase from 0 to 90 to 180 to 270 to 360 degrees. ASSRs are plotted so that their amplitude is reflected as the length of a line that starts at the center of the graph (filled circle in Figure 2–1) and extends outward as a function of its size. The polar plot in the figure shows three ASSRs in the upper right

[1]The enterprising reader may note the use of the square root of values reported in statistical tables showing critical values of the F-distribution. The square root of these values is used because the F-ratio estimates of signal and noise are reported in terms of amplitude, rather than power. Also, 2 and 2*n* degrees of freedom, rather than 1 and *n*, are used because the amplitudes of the signal and noise are estimated from measures computed using both amplitude and phase (for detailed discussion, see Lins et al., 1995).

[2]With use of 16 frequencies (i.e., 8 above and 8 below the frequency of ASSR), the F-ratio criterion increases to 1.82 (for 0.05, at 2 and 32 degrees of freedom), because this estimate will be more noisy than one obtained by averaging the values of 120 frequencies together. Although the F-ratio has been increased, this test is not more conservative. The F-ratio criterion is merely increased to compensate for less bins being used in the noise estimate. The only way to make the F-ratio more conservative is to increase the statistical criterion for a given degrees of freedom (require $p < .01$ instead of $p < .05$). This has been a source of some confusion. Studies have shown that changing the number of frequencies that contribute to the noise estimate does not lead to differences in detection efficacy when the significance level is held constant (e.g., Valdes et al., 1997).

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corner, wherein response 'A' represents an ASSR with a phase of 15 degrees and an amplitude of 50 nanovolts (nV); response B represents an ASSR with a phase of 45 degrees and an amplitude of 60 nV; and response C represents an ASSR for which the reader is now encouraged to provide an estimated value.[3] The ASSRs seem to be clustered in the upper right quadrant, rather than residing in all four quadrants, and a phase statistic may be used to formally determine if this intuitively nonrandom distribution is statistically improbable at a specified probability level, such as $p < .05$. As in the case of the amplitude statistic, as the number of phase values that are assessed increases (i.e., degrees of freedom increases), the value of the statistical test criterion may become smaller, although the p value needed to reach significance will remain at a set probability level (e.g., $p < .05$).

Stimulus Considerations

Creation of Auditory Steady-State Stimuli

A large number of stimuli have been used for evoking ASSRs. Figure 2–2 shows six examples of such stimuli, each having different advantages and disadvantages. The first stimulus is a sinusoidally amplitude-modulated (AM) 1000-Hz tone for which the frequency of modulation (Fm) is 80 Hz. The amplitude spectrum shows that this stimulus has energy at the 1000-Hz carrier frequency (Fc), and at two sidebands located at the Fc ± Fm. When the modulation depth is 100%, which causes the amplitude envelope to decrease to zero every cycle of the modulator, the sidebands are only 50% of the amplitude of the carrier. The second stimulus is a mixed-modulation (MM) stimulus in which both amplitude and frequency modulation occur at 80 Hz. The amplitude modulation depth commonly is set at 100%. Frequency modulation depth often is set at about 20%, which means that the stimulus roves ±10% from the center carrier frequency (Cohen, Rickards, & Clark, 1991; John, Dimitrijevic, & Picton, 2003). Because adjusting the maximum frequency (of the FM glide) to coincide with the maximum amplitude (of the AM envelope) generally evokes the largest ASSR, the spectral power of the stimulus is shifted by about 100 Hz to be slightly higher than the 1000-Hz center frequency (arrow labeled "Shift" in Figure 2–2). Although it is possible to compensate for this shift by defining the center frequency to be slightly lower than 1000 Hz, this usually is not done. The MM stimulus still is fairly frequency-specific, because the amplitudes of the extended sidebands drop off rapidly from the central frequency. The MM stimulus tends to elicit larger responses (in adults for 500, 1000, and 2000 Hz stimuli, and in infants for 1000 and 2000 Hz) than those occurring with use of amplitude modulation (the ASSRs are about 20% larger than when using simple AM stimuli) or frequency modulation alone (John, Brown, Muir, & Picton, 2004). The third type of stimulus is an exponential AM stimulus, in which the sine wave envelope has been raised to a power of 2 (i.e., squared). Exponential AM stimuli are similar to conventional AM stimuli except that their rising and falling slopes are steeper, causing a slight decrease in its acoustic spectral specificity. Exponential stimuli have been shown to produce

[3]The ASSR for C has a phase of 80 degrees and amplitude of 40 nV.

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CHAPTER 3

The Stimulus-Response Relationship in Auditory Steady-State Response Testing

DAVID W. PURCELL
HILMI R. DAJANI

This chapter explores how the auditory steady-state response (ASSR) changes with the stimulus that is used to elicit it. In the previous chapter, a variety of stimuli were described, such as amplitude-modulated (AM) tones, tone pairs, repeated clicks and tone bursts, and more complex waveforms that include a combination of amplitude and frequency modulation. The effects of these different stimulus types are discussed next, but it is important to recognize that in general, the stimuli used to elicit ASSRs share three defining parameters that play important roles in the response. These three stimulus parameters in common are rate, intensity, and carrier frequency.

The *rate* is the frequency at which the stimulus varies in amplitude, frequency, or both. For AM or frequency-modulated (FM) stimuli, rate refers to the modulation frequency. For tone pairs that cause beating, rate refers to the rate of the beat, or fluctuation in amplitude envelope, which is the difference in frequency between the two carrier tones. Finally, for click or tone burst stimuli, rate is the frequency of stimulus repetition. Rate is particularly important because it is the frequency at which the

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response is evaluated in the spectrum of the averaged electroencephalogram (EEG) sweeps. Because many common stimuli include explicit amplitude modulation, this chapter generally refers to rate as the *modulation frequency*.

The most familiar of the three common stimulus parameters is *intensity*, which, as it normally does, refers to the root-mean-square (RMS) level of the presented stimulus specified with a decibel scale such as dB SPL (sound pressure level), dB HL (hearing level), or dB SL (sensation level). Finally, the *carrier frequency* is the frequency of the sinusoid to which modulation is applied. By specifying the carrier frequency, the response can be initiated from a desired characteristic region in the tonotopic cochlea. Sometimes broad-band noise is used instead of a tone, in which case there is no carrier frequency, but rather a noise carrier. This chapter describes the effects of these parameters in detail.

Many clinical instruments use ASSRs elicited by stimuli whose modulation rates are unique to each ear. Analysis of the average EEG spectrum then typically treats responses from the two ears as independent. However, the ASSR also can be elicited using identical modulation rates in each ear simultaneously. This allows these binaural measurements to be compared with monaural measurements elicited by the same stimulus. Alternatively, dichotic unmodulated stimuli can be presented to each ear. The response then relies on interactions in the auditory nervous system to produce modulation through binaural beating. These methods allow binaural interactions to be studied. This chapter discusses the binaural techniques that have been developed and their potential value for future clinical use.

Modulation Rate

In humans, the effect of modulation rate on the ASSR has been investigated over a broad frequency range: from about 2 Hz up to about 600 Hz (e.g., Campbell, Atkinson, Francis, & Green, 1977; Cohen, Rickards, & Clark, 1991; Galambos, Makeig, & Talmachoff, 1981; Geisler, 1960; Rickards & Clark, 1984; Rees, Green, & Kay, 1986; Stapells, Linden, Suffield, Hamel, & Picton, 1984). When all other stimulus parameters are held constant, the amplitude and phase of the ASSR varies with modulation rate. Figure 3–1, reproduced here from a report by Picton, John, Dimitrijevic, and Purcell (2003; their Figure 10), plots data from many studies that looked at different ranges of modulation. These studies did not use uniform carrier frequencies or stimulus levels, but the plots show the general effect of modulation rate on the amplitude of the response. It can be seen that at very low frequencies (below 10 Hz), and in the region of 40 Hz, the response is at its largest. Another, smaller amplitude peak is evident in the range 80 to 100 Hz, after which the response decreases towards both zero and the noise floor at higher modulation rates.

Most investigations of modulation rate have used sequential measurements wherein the modulation rate (as well as all other stimulus parameters) is fixed during a given measurement and then changed in between measurements. This is because the Fourier transform typically used in the analysis requires there to be no changes in stimulus or response for optimal performance. Using other analysis techniques, however, does make it possible to change a stimulus parameter, such as modulation, within a given measurement. By ramping or sweeping

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CHAPTER 6

Clinical Application of Auditory Steady-State Responses

GARY RANCE
BARBARA CONE-WESSON

Auditory Evoked Potentials in Clinical Practice

Since auditory evoked potentials (AEPs) were first identified, attempts have been made to incorporate the auditory pathway insights they offer into clinical practice. Current applications can essentially be divided into three categories:

- Estimation of hearing threshold
- Differential diagnosis
- Auditory processing

Estimation of Hearing Threshold

To date, the major clinical application for the auditory steady-state response (ASSR) has been the objective estimation of hearing levels. The clinical populations that may potentially require this form of assessment fall broadly into two groups: (1) adults and children older than 6 to 9 months of age who are unable (as a result of physical, intellectual, or emotional problems) or unwilling (for financial or other reasons) to provide accurate audiometric results and (2) infants and

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young children who are too immature to be conditioned for audiometric assessment. Evaluation of the second of these groups has been the primary focus of much of the clinical ASSR research effort over the past decade. The importance of early identification and management of congenital hearing loss is now well established. Provision of sound at audible levels (through hearing aids or other means) in the first months of life can minimize degenerative processes in the central auditory pathways (Sharma, Dorman, & Spahr, 2002) and can, in combination with appropriate family and educational support, maximize long-term speech and language outcomes (Moeller, 2000; Yoshinga-Itano, Sedley, Coulter, & Mehl, 1998). Newborn hearing screening programs have resulted in an increase in the number of newborns diagnosed with hearing loss (Kennedy & McCann, 2004; Thompson, McPhillips, Davis, Lieu, Homer, & Helfand, 2001). Identification of affected children is of course only the first step in the diagnostic process, and the significant challenge currently facing auditory clinicians is to accurately quantify hearing levels in these very young babies so that appropriate intervention strategies can be implemented. Various aspects of ASSR generation and recording make the response a good candidate (in theory at least) for an objective measure of hearing. First, there are a number of potential advantages related to the types of stimuli used to generate the response. Unlike some transient AEPs that require short-duration signals (such as acoustic clicks or brief tone bursts) to produce sufficiently synchronized neural activity, the ASSR can be elicited by reasonably frequency-specific stimuli such as continuous-amplitude or amplitude- and frequency-modulated (AM-FM) tones. This frequency specificity, coupled with the fact that ASSRs can be evoked by carrier tones across the audiometric range, allows the possibility of generating "evoked potential audiograms" that reflect the audiometric configuration of the subject. The ability to elicit the ASSR with continuous stimuli has a number of other potential advantages. Continuous modulated tones more closely resemble the pure tones used in audiometric testing (than do brief tone bursts or click stimuli). Behavioural detection thresholds for continuous modulated tones, for example, are typically within 1 to 2 dB of American National Standards Institute (ANSI) reference levels and, as such, are usually presented in the same units (dB HL). Brief stimuli, by contrast, require a correction factor (to compensate for their brevity), which creates the potential for calibration error if the correction (which is based on average behavioural detection thresholds in normal-hearing adults) is not appropriate for every subject.

Furthermore, continuous AM or AM/FM tones may be delivered with a presentation level range similar to that of pure tones. Maximum presentation levels for most test frequencies in the audiometric range may be as high as 120 dB HL, allowing for the possibility of assessment of hearing levels in the profound range (Rance, Dowell, Beer, Rickards, & Clark, 1998). By contrast, calibration corrections (accounting for differences in temporal summation for brief- versus long-duration stimuli) limit the maximum presentation levels available for tone-burst testing to approximately 100 to 110 dB nHL (Stapells, Picton, Durieux-Smith, Edwards, & Moran, 1990). Although 100 dB nHL is equivalent to a peak equivalent SPL of 120 or 125 dB, it appears

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that the AM-FM tones used for ASSRs may be more effective than transients for estimating minimal residual hearing.

As discussed in previous chapters, the ASSR can be extracted mathematically from within the electroencephalogram (EEG), and response presence or absence can be determined statistically using measures such as phase- or magnitude-squared coherence or analysis of variance of the response spectrum. These features obviously are desirable from a clinical implementation perspective in that they offer the possibility of truly objective assessment procedures, removing the need for clinicians (with varying degrees of experience in waveform detection) to visually interpret averaged EEG tracings. When coupled with algorithms or regression formulae for estimating behavioural threshold from ASSR threshold, it is plausible that the ASSR test and its interpretation could be completely automated.

Another potential advantage afforded by the ASSR analysis technique relates to the ability to record more than one response at the same time. Independent ASSRs to a number of stimulus tones can be elicited simultaneously, provided that the center frequencies of the signals are sufficiently different (i.e., separated by at least one octave) and that the tones are modulated at different rates (Lins & Picton, 1995). Up to eight stimuli configured in this way (four tones presented to each ear) have been used to simultaneously elicit ASSRs (John, Lins, Boucher, & Picton, 1998). Although this does not necessarily allow an eightfold reduction in test time, the ability to record multiple responses offers the potential for significant clinical efficiencies that have great appeal, particularly for assessing subjects in natural or sedated sleep.

Differential Diagnosis

Determining the site (or sites) of abnormality for patients presenting with hearing-related problems is one of the particular challenges facing auditory clinicians. Differentiating between pathologic conditions occurring at different points along the auditory pathway—from peripheral disorders affecting the external or middle ear conductive mechanisms to cochlear abnormalities and central nervous system disturbances—has been the focus of a substantial body of transient AEP research over the past decades. Assessment techniques using compound action potentials, auditory brainstem response, auditory middle latency response, and cortical AEPs can be used to evaluate the afferent auditory nervous system.By contrast, application of the ASSR as a tool for differential diagnosis, or even the development of a working understanding of how different (central) pathologies might affect the response, is only just beginning. Recent work has considered the distinction between peripheral and cochlear dysfunction (see Chapter 11 for details) and the influence of neural synchrony disorders such has auditory neuropathy/dyssynchrony on the response has been noted (Rance et al., 1999). Shinn (2005) found large discrepancies between behavioural threshold and ASSR threshold in 11 adults with neurologic lesions of the brainstem or cortex confirmed by magnetic resonance imaging (MRI). In neonates with a history of extreme prematurity and risk for neurologic impairment, Cone-Wesson, Parker, Swiderski, and Rickards (2002) also found an exceptionally high incidence of elevated ASSR thresholds. However, detailed and extensive investigation of the effects on the

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ASSR of central disorders such as intracranial tumors and neoplasms and the various disease processes that affect the central auditory pathways is yet to be undertaken.

Auditory Processing

The ability to objectively measure auditory processing skills is highly desirable in clinical populations involving subjects unable to provide reliable volitional responses to auditory stimuli. Transient AEPs such as the P300 and mismatched negativity (MMN) response have been used (with varying degrees of success) in such groups as metrics for a range of abilities including auditory discrimination, information processing, memory, and attention (Davis, 1964; Näätänen, Gaillard, & Mäntysalo, 1978; Sutton, Tueting, Zubin, & John, 1965).

Assessment of auditory processing abilities using the ASSR is another area yet to be fully explored. Preliminary work has, however, pointed to potential applications involving both basic feature level discrimination and processing of complex stimuli. A number of authors have for example, measured ASSRs to AM stimuli with different modulation depths and rates (John, Dimitrijevic, Van Roon, & Picton, 2001; Purcell, John, Schneider, & Picton, 2004) with a view to providing objective correlates of temporal resolution ability. ASSRs also may provide insights into spectral processing when responses are elicited by frequency rather than by amplitude modulation or when dynamic response changes are generated by variations in carrier frequency (Patel & Balaban, 2004). In addition to these auditory discrimination applications, the ASSR technique, by virtue of its ability to elicit multiple responses to complex stimuli, may offer insights into a subject's overall processing capacity. For example, Dimitrijevic and colleagues (2002) presented multiple simultaneous tones and considered the number of independent responses obtained to be a reflection of the amount of information available in the central auditory pathways for processing of complex signals (such as speech).

A comprehensive discussion of the current research relating to ASSR assessment of suprathreshold hearing in both adults and children is provided in Chapter 12 of this book.

From the Laboratory to the Clinic

Translating the insights obtained in the laboratory setting into clinical practice poses a number of challenges. Where assessment in an experimental context typically involves relaxed and cooperative subjects of well-defined hearing status, clinicians are faced with patients of all ages presenting with a range of (often undiagnosed) dysfunctions. Assessment techniques need to be robust and able to provide accurate (or at least predictable) results in a wide range of circumstances. In particular, successful clinical application of the ASSR (as with any AEP technique) requires answers to the following questions:

- Can the ASSR be reliably recorded in subjects of all ages?
- What effect does auditory pathway maturation have on the ASSR, and

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what is the time course of developmental effects?

- How does subject state (natural sleep/sedation/general anesthesia) affect the response?
- What are the optimal test parameters (e.g., modulation rate, stimulus type) for response generation in different subject groups?
- What is the most reliable way to predict hearing threshold from ASSR findings (e.g., correlation of ASSR-behavioural hearing thresholds, extrapolation from amplitude/intensity functions)?
- Can reliable results be obtained within a manageable test time?
- What is the relationship between ASSR findings and behavioural hearing levels in normal-hearing adult subjects?
- Is this relationship different in hearing-impaired subjects, and does the accuracy of hearing level estimation vary with degree and type of hearing loss?
- Apart from hearing level, what factors (such as site of lesion, subject age, and so on) may affect the ASSR-hearing threshold relationship?
- How does hearing threshold prediction using the ASSR compare with other (transient) AEPs in different populations?
- Does the ASSR have any neurodiagnostic value for identification of central auditory pathway disorders (e.g., acoustic tumors, auditory neuropathy/dys-synchrony)?
- Can the ASSR be used for auditory processing applications?
- Can the ASSR be used to measure device function (amplification/cochlear implant)?

Outlining the ways in which these questions have been approached over the last 2 decades, and the degree to which they have been satisfactorily answered is the focus of the remaining chapters in this book.

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CHAPTER 8

The 80-Hz Auditory Steady-State Response Compared with Other Auditory Evoked Potentials

DAVID R. STAPELLS

Introduction

As clearly indicated in other chapters of this book, there is much interest in audiologic applications of the auditory steady-state response (ASSR) to stimuli modulated with rates between 70 and 110 Hz (the "80-Hz ASSR"), especially for threshold estimation in infants and young children with hearing loss. This heightened interest is well justified. Nevertheless, in certain circumstances, other auditory evoked potential (AEP) measures may be more appropriate. Furthermore, some comparisons of the 80-Hz ASSR with other AEPs may not have been made under equivalent circumstances and are thus still unresolved, especially related to the tone-evoked auditory brainstem response ("tone-ABR"). Finally, as a "brainstem" response, the 80-Hz ASSR is limited in what it can tell us about auditory processing—obtaining measures from anatomically and hierarchically higher areas of the auditory system may prove informative for normal and disordered functions. This chapter considers the 80-Hz ASSR relative to the tone-ABR, the 40-Hz ASSR, and the slow cortical potential (SCP).

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Basic Principles

Keeping Apples with Apples: Compare only Thresholds For Techniques Using Frequency-Specific Stimuli

The recent literature is replete with studies that compare thresholds for the 80-Hz ASSR (to frequency-specific tonal stimuli) with those for the click-evoked ABR. Comparing clicks, a completely non–frequency-specific stimulus (typically with equal energy from less than 0.1 kHz to approximately 6 to 8 kHz), with narrow-band, sinusoidally amplitude-modulated (AM) tones is equivalent to comparing apples and oranges. Those frequencies that dominate a particular subject's click-ABR cannot be determined with certainty; this is especially true when hearing loss is present. This chapter, therefore, considers only results for frequency-specific measures.

There is More Than One "ASSR"

A reading of the ASSR literature since 1996 may lead to the erroneous impression that there is only one "ASSR." However, the ASSR is not a unitary response. Use of different modulation rates, if the difference is large enough, results in responses dominated by different regions of the brain. Moreover, because they reflect overlapped responses, the ASSRs typically reflect contributions from a wide area of the auditory system. For example, the 80-Hz ASSR is primarily brainstem in origin but contains some cortical contribution; the 40-Hz ASSR has both brainstem and cortical generators, with the cortex dominating in awake adults; responses to slow rates (less than 20 Hz) are likely to be dominated by cortical sources but must contain brainstem contributions (Herdman et al., 2002). As described in this chapter, the ASSRs to different rates often have quite different properties (and different uses), so ASSRs cannot be considered as a single response.

Comparisons of the 80-Hz Auditory Steady-State Response and Tone-Evoked Auditory Brainstem Response

Considering the clear relevance of the 80-Hz ASSR to infant audiometry, there are surprisingly few comparisons of tone-ABR and 80-Hz ASSR thresholds in the same individuals, and especially in infants with hearing loss. Such studies are faced with two major differences between these techniques: (1) The ASSR is detected objectively by a computer using frequency-based measures, whereas the tone-ABR is detected by a clinician observing the visual replication of responses and thus is subjective in nature; and (2) ASSR stimuli are typically continuous and calibrated in dB HL, whereas tone-ABR stimuli are brief in duration and calibrated in "nHL." In the latter situation concerning calibrations, such differences may potentially be overcome by (1) determining differences in acoustic terms, such as *peak-to-peak equivalent* (ppe) SPL, and, (2) when assessing listeners with impaired hearing, by using predictive formulae and correlation coefficients determined using the relevant metric (i.e., nHL and HL).

In normal adults, whether 80-Hz ASSR thresholds are better than tone-ABR

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CHAPTER 9

Auditory Steady-State Responses in Neonates and Infants

GARY RANCE

Introduction

As the developmental course of the auditory pathway is not consistent along its length (Goodin, Squires, Henderson, & Starr, 1978; Ponton, Egermont, Kwong, & Don, 2000), the reliability of auditory steady-state response (ASSR) measurement in children is highly dependent on the neural generators involved and, hence, on the stimulus presentation rate. The ASSR elicited by signals at 40 Hz (the "40-Hz response"), which in awake adult subjects can be detected at levels close to hearing threshold (Boettcher, Poth, Mills, & Dubno, 2001; Tomlin, Rance, Graydon, & Tsialios, 2006; Van Maanen & Stapells, 2005), is not consistently recordable in young children (Levi, Folsom, & Dubie, 1993; 1995; Maurizi et al., 1990; Stapells, Galambos, Costello, & Makeig, 1988). There are two main reasons for this. The first relates to the practicalities of pediatric testing. Obtaining recordings with acceptably low levels of electroencephalogram (EEG) noise in youngsters requires that they be in either natural or sedated sleep. Unfortunately, in both sleeping adults and children, the amplitude of the 40-Hz response is reduced to less than 50% of that obtained in awake subjects (Cohen, Rickards, & Clark, 1991; Levi et al., 1993; Pethe, von Specht, Muhler, & Hocke, 2001; Petitot, Collet, & Durrant, 2005; Plourde &

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Picton, 1990), so response thresholds are significantly higher (Galambos, Makeig, & Talmachoff, 1981; Klein, 1983; Picton, Vajsar, Rodriguez, & Campbell, 1987). Picton and colleagues (1987), for example, recorded ASSRs to 500-Hz tones in adult subjects (tested awake and asleep) and found that responses generally were less reliable, and detection thresholds were on average 11 dB higher, during sleep. This subject state effect is not surprising, because transient auditory evoked potentials with similar latencies to those of the 40-Hz ASSR (approximately 30 ms) are also affected by sleep and sedation (Osterhammel, Shallop, & Terkildsen, 1985).

The second major limitation on the recording of the 40-Hz ASSR in children is that the response is immature not only in infancy but also through the first decade of life. While the developmental course of this response is yet to be fully determined, Aoyagi and colleagues (1994) did show a general increase in detectability in subjects 6 months to 15 years of age, and Pethe, Muhler, Siewert, and von Specht (2004) found amplitude increases throughout childhood, with the response not reaching adult proportions until around the age of 14 years.

The amplitude of the infant ASSR decreases with increasing presentation rate (as does the adult response), but unlike adults, young children do not show an enhancement for modulation frequencies around 40 Hz (Aoyagi et al., 1994; Levi et al., 1993; Riquelme, Kuwada, Filipovic, Hartung, & Leonard, 2006; Suzuki & Kobayashi, 1984). The infant ASSR at 40 Hz, for example, is around half the size of the response at 10 Hz, whereas the adult ASSR is about 50% larger.[1] The lack of amplitude enhancement at 40 Hz in children suggests that the auditory cortex (the approximate region of origin for this response) is immature and unable to support the ASSR at high rates. Comparable results have been demonstrated in transient auditory evoked potentials of similar latency. Jerger, Chmiel, Glaze, and Frost (1987), for example, also found that middle latency responses (MLRs) could only be recognized in young children for stimuli at very low (less than 2 Hz) presentation rates.

Unlike the 40-Hz response, ASSRs to stimuli presented at rates of approximately 70 to 100 Hz can be recorded in children of all ages including newborns (Aoyagi et al., 1993; Cone-Wesson, Parker, Swiderski, & Rickards, 2002; John, Brown, Muir, & Picton (2004); Levi et al., 1993; Lins & Picton, 1995; Luts, Desloovere, & Wouters, 2006; Rance, Tomlin, & Rickards, 2006; Rance et al., 2005; Rickards et al., 1994; Savio, Cardenas, Perez-Abalo, Gonzalez, & Valdes, 2001). These "high-rate" ASSRs, which show equivalent latencies around 10 ms, are better suited to pediatric application in that they are appear to be unaffected by response state (Cohen et al.,1991; Linden, Campbell, Hamel, & Picton, 1985; Levi et al., 1993; Rance, Rickards, Cohen, De Vidi, & Clark, 1995) and less affected by developmental factors, at least in children younger than 12 months of age at assessment. Recent findings, however, have pointed to some maturational changes in the first year of life, and it is these developments (and their clinical implications) that are the focus of this chapter.

[1]This does not necessarily mean that response detectability in babies is greater for frequencies around 10 Hz, because background EEG levels typically are higher in this region (Riquelme et al., 2006).

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Auditory Steady-State Response Development in Normal Babies

Maturation of high-rate ASSRs occurs through the neonatal and infant periods. Response latency delays have been reported in neonates (Cone-Wesson, Parker, et al., 2002; Rickards et al., 1994), and more importantly, a number of recent studies have shown that ASSR amplitudes are significantly lower (relative to adults and older children) for normal infants in the first year of life.

The Neonatal Auditory Steady-State Response

The amplitude of the high-rate (greater than 70 Hz) ASSR in the neonatal period is highly variable across subjects and is generally considerably smaller than that observed in older subjects (John et al., 2004; Luts et al., 2006). Table 9–1 shows average response amplitudes obtained across a range of carrier frequencies for babies tested within 3 days of birth in the study by John and associates, and at an average corrected age of 12 days in the investigation by Luts and colleagues (2006).

The test stimuli used in these two studies were slightly different—in the former, tonal stimuli with an exponential envelope, and in the latter, sinusoidally modulated mixed amplitude- and frequency-modulated (AM/FM) tones.[2] Both investigations, however, revealed average response levels of only 10 to 20 nV for stimuli at 50 dB SPL. These response amplitudes are significantly lower than those obtained using identical test methodologies in normally hearing adult subjects. John, Dimitrijevic, and Picton (2002), for example, found adult responses approximately twice that of the newborn level (approximately 35 nV); Luts and associates (2006) found response amplitudes approximately three to four times higher in their group of adult controls (Table 9–1). Figure 9–1 demonstrates this response amplitude difference, showing the averaged amplitude spectrum obtained (in this case to stimuli at 30 dB SPL) for groups of infant and adult subjects (Luts et al., 2006).

Table 9–1. Average neonatal ASSR amplitudes (nV) obtained for simultaneous stimuli at the audiometric octave frequencies at a presentation level of 50 dB SPL

Study	500 Hz	1000 Hz	2000 Hz	4000 Hz
John et al., 2004 (newborns)	17.5 ± 13.7	20.6 ± 11.2	22.4 ± 9.3	15.3 ± 5.6
Luts et al., 2006 (newborns)	9 ± 6	12 ± 7	11 ± 5	8 ± 5
Luts et al., 2006 (adults)	32 ± 15	51 ± 18	45 ± 15	22 ± 11

[2]A discussion of the types of stimuli used to elicit the ASSR in babies can be found in Chapters 2 and 3.

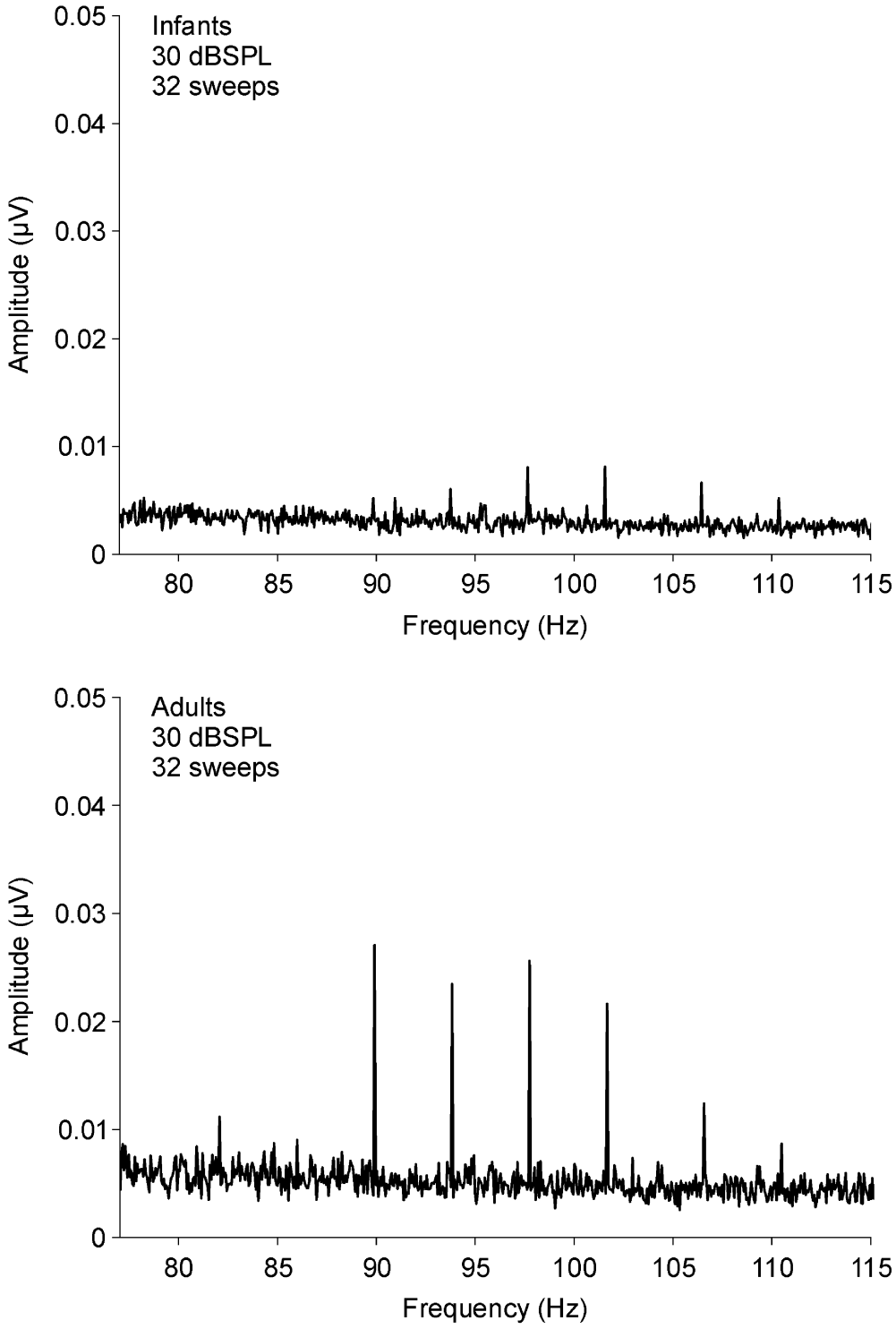

Figure 9–1. Averaged amplitude spectrum at 30 dB SPL for eight normal-hearing infants and adults (both ears). (Figure 3 from Luts et al. [2006]. *Audiology & Neuro-otology*, *11*, 24–37. Copyright 2006 Karger. Reproduced with permission.)

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CHAPTER 14

Case Studies in Application of Auditory Steady-State Response Testing

Case Study 1 Auditory Evoked Potential Assessment of a Child with Multiple Disabilities

Author: Gary Rance
Affiliation: University of Melbourne

Subject History

Subject A was born at 27 weeks postconceptual age. Her weight at delivery was 930 g. She spent 6 weeks in neonatal intensive care (requiring oxygen support for 5 weeks) and then remained in hospital for an additional 6 weeks in a special care environment. Subject A was subsequently diagnosed with athetoid cerebral palsy, thought to be a consequence of her prematurity and rocky neonatal course.

Results

Hearing assessment was undertaken at the University of Melbourne School of Audiology Clinic when Subject A was 19 weeks of age (6 weeks corrected). Initial testing was carried out with the child awake but resting quietly on her mother's lap. Behavioural observation assessment revealed no obvious response to a range of speech and noisemaker stimuli presented in the free field at maximum levels of approximately 70 to 80 dBA. A repeatable "eye widening" response was observed to a drum beat at 95 dBA and above, but no aural palpebral reflex could be elicited at 105 dBA. These findings are difficult to interpret in a 2-month-old child (particularly one with cerebral palsy) but are broadly consistent with conductive or mixed loss of mild degree or greater, or significant

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sensorineural deficit of at least moderate degree. Impedance audiometry (1000-Hz probe tone) showed type A tympanograms, suggesting normal middle ear function bilaterally.

Evoked potential testing was carried out using systems custom built at the University of Melbourne Department of Otolaryngology, as detailed by Rance and colleagues (Rance, Dowell, Beer, Rickards, & Clark, 1998).[1] The assessments took place in a sound-treated room with the child in natural sleep, using the procedures outlined by the investigators in (Rance et al., 1998). For auditory brainstem response (ABR) testing, alternating-polarity, 100 s clicks were presented at a rate of 11 Hz. Auditory steady-state responses (ASSRs) were elicited by amplitude- and frequency-modulated (AM/FM) tones at octave frequencies from 500 Hz to 4 kHz. The modulation rate for each carrier tone was 90 Hz. Response threshold (for both ABR and ASSR testing) was established by increasing stimulus presentation level in 10-dB steps from 60 dB HL until a response could be detected, and then decreasing the level in 5-dB steps until the auditory evoked potential (AEP) was no longer recordable.

Click-ABR assessment in this case showed response waveforms to air conducted stimuli at left levels 75 dB nHL and above for the left ear and 80 dB nHL and above for the right ear. These results are consistent with mid- to high-frequency hearing loss of moderate-to-severe degree bilaterally (Stapells et al., 1994). No response was observed to unmasked, bone-conducted clicks at the maximum presentation level (50 dB nHL), indicating that the loss in each ear was primarily of sensorineural origin.

ASSR testing showed thresholds at levels around 70 to 80 dBHL for test frequencies across the audiometric range (Figure 14–1.1). As such, the findings were consistent with the click-ABR (and behavioural) results and suggested flat-configuration hearing loss at moderate-to-severe levels bilaterally.

Based on these results, Subject A was referred for hearing aid fitting and early intervention support. Behind-the-ear devices were fit bilaterally at the (corrected) age of 3 months, with amplification levels set conservatively, assuming hearing levels 10 to 15 dB better than the ASSR thresholds. (Data generated in the 15 years since this child was assessed would suggest that her hearing levels were most likely to be only about 5 dB better than ASSR threshold [see Chapter 7], but at the time, there was only limited data correlating ASSR and behavioural threshold in hearing-impaired babies.) Subject A tolerated her hearing aids well and by 6 months of age was reported by the family and teacher of the deaf to be showing consistent responses to speech at normal voice levels.

By 17 months of age however, Subject A's responses had become sporadic, and her family and clinicians began to doubt that she was receiving optimal input from the hearing aids. Attempts to carry out conditioned audiometric testing had been unsuccessful because of her severe physical difficulties. She was at this point unable to sit without support, had very limited head control, and showed mixed muscle tone (a combination of hyper-

[1]Assessment of this child (in the early 1990s) predated the development of commercial ASSR systems.

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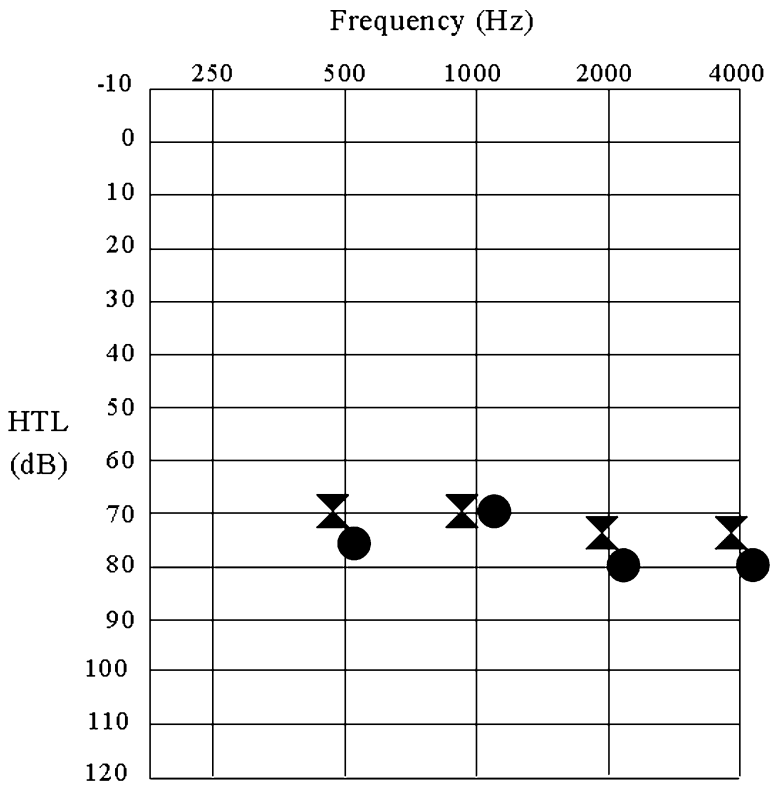

Figure 14–1.1. ASSR threshold levels obtained at the age of 6 weeks for the left (*filled crosses*) and right (*filled circles*) ears.

and hypotonia) with involuntary movements. As such, objective hearing assessment was organized.

ASSR testing was repeated at the age of 18 months. Subject A was not inclined to fall asleep in the clinical setting, so the assessment was carried out with the child under sedation (with chloral hydrate in a dose of 50 mg/kg of body weight).[2] ASSR thresholds for each ear were consistent with those obtained previously, suggesting stable hearing levels bilaterally (Figure 14–1.2).

At 12 years of age, Subject A was a consistent hearing-aid wearer who was reportedly more comfortable when aided than when not. Her physical limitations had continued to make conditioned audiometric assessment difficult, and only approximate behavioural hearing levels could be determined. A further AEP assessment was therefore undertaken.

[2]The effect of sedation (and general anesthetic) on the high rate ASSR is yet to be fully explored. If there is a response threshold difference between sedated and natural sleep, it appears to be minimal (Rance et al., 1995). Response sensation levels in sedated subjects may, if anything, be slightly reduced, because EEG noise levels are comparatively low.

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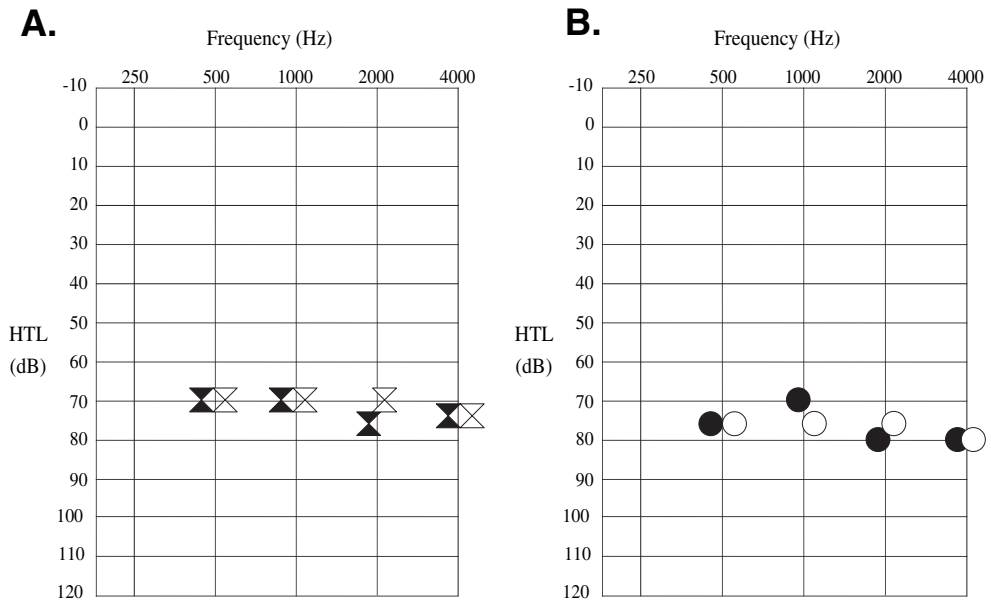

Figure 14–1.2. A, ASSR threshold levels obtained for the left ear at 6 weeks (*filled crosses*) and at 18 months (*unfilled crosses*). **B**, ASSR threshold levels obtained for the right ear at 6 weeks (*filled circles*) and at 18 months (*open circles*).

On this occasion she was tested awake using ASSR and cortical auditory evoked potentials (CAEP).

These assessments were carried out using the GSI Audera system. The stimuli for ASSR testing were AM/FM tones modulated at a rate of 40 Hz. CAEPs were elicited by Blackman-gated tone bursts (5:40:5 cycles) presented at a rate of 0.7 Hz. Stimulus step size (around threshold) for both tests was 5 dB.

Movement- and muscle-related artifact did hamper response recording at times. However, repeatable 40 Hz ASSR response thresholds were obtained at levels around 70 to 75 dB HL (Figure 14–1.3). CAEP thresholds were obtained at similar levels. Figure 14–1.4 shows the averaged electroencephalogram (EEG) tracings for 500-Hz tone bursts presented to each ear. The lowest presentation level at which the P1/N1 waveform complex could be identified in each case was 70 dB nHL. Thus, the 40-Hz ASSR and CAEP findings were consistent with each other and match the evoked potential findings for this child across the first decade of life.

Outcomes

Subsequent behavioural hearing tests (performed when she was 15 years of age) have confirmed the AEP findings for Subject A, indicating a flat configuration, sensorineural hearing loss of moderate degree (see Figure 14–1.3). She remains a consistent hearing aid user, is responsive to familiar voices and has shown evidence of receptive understanding. Expressive (spoken) language development has, however, been limited.

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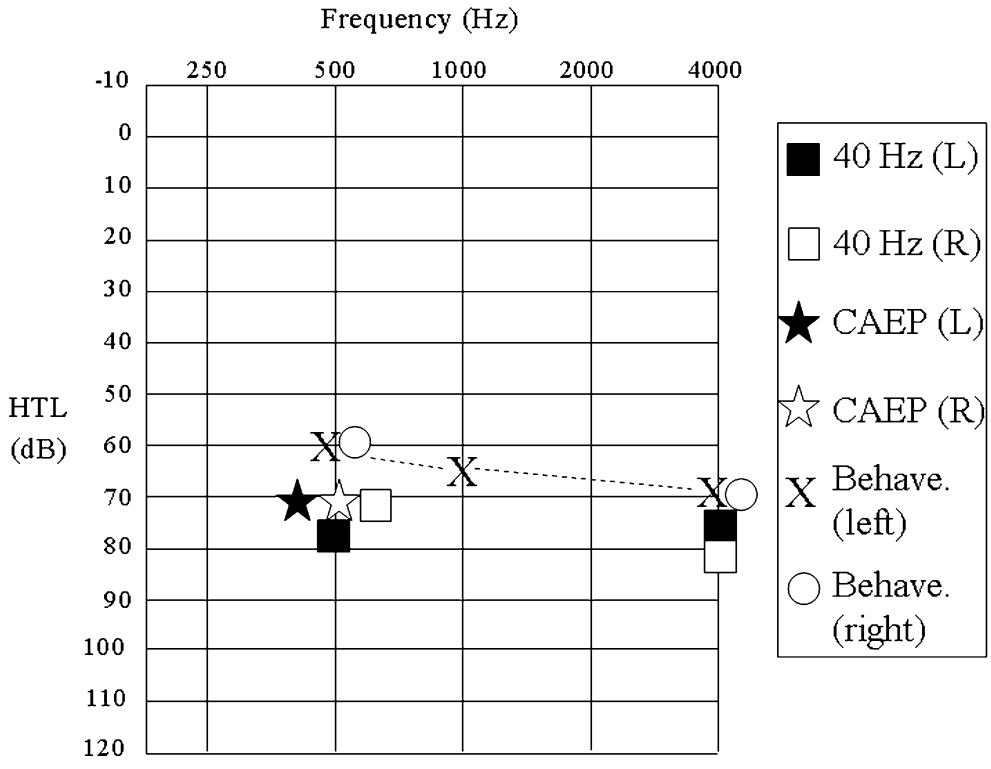

Figure 14–1.3. 40-Hz ASSR and CAEP thresholds (recorded at the age of 12 years) and conditioned behavioural hearing thresholds (recorded at the age of approximately 14 to 15 years).

Comments

This study provides an example of the way in which a battery of tests can be used to estimate hearing level in a child unable to provide an accurate audiogram. Converging evidence from multiple sources (both behavioural and electrophysiological) in this case provided a solid basis for intervention at a young age.

One of the features of this study was the consistency of the ASSR findings across an extended (12-year) assessment period. Almost identical response thresholds were obtained when the child was tested at 6 weeks of age and then again at 18 months. This result is consistent with the (limited) clinical evidence, suggesting that ASSRs can be recorded at consistently low sensation levels in neonates and young babies with sensorineural hearing loss (Luts, Desloovere, & Wouters, 2006; Rance, Rickards, Cohen, De Vidi, & Clark, 2005).[3] Infants with normal hearing, by contrast, show significant maturational changes and would

[3]The observation that ASSR sensation levels have not changed across assessments assumes that Subject A's hearing has been stable.

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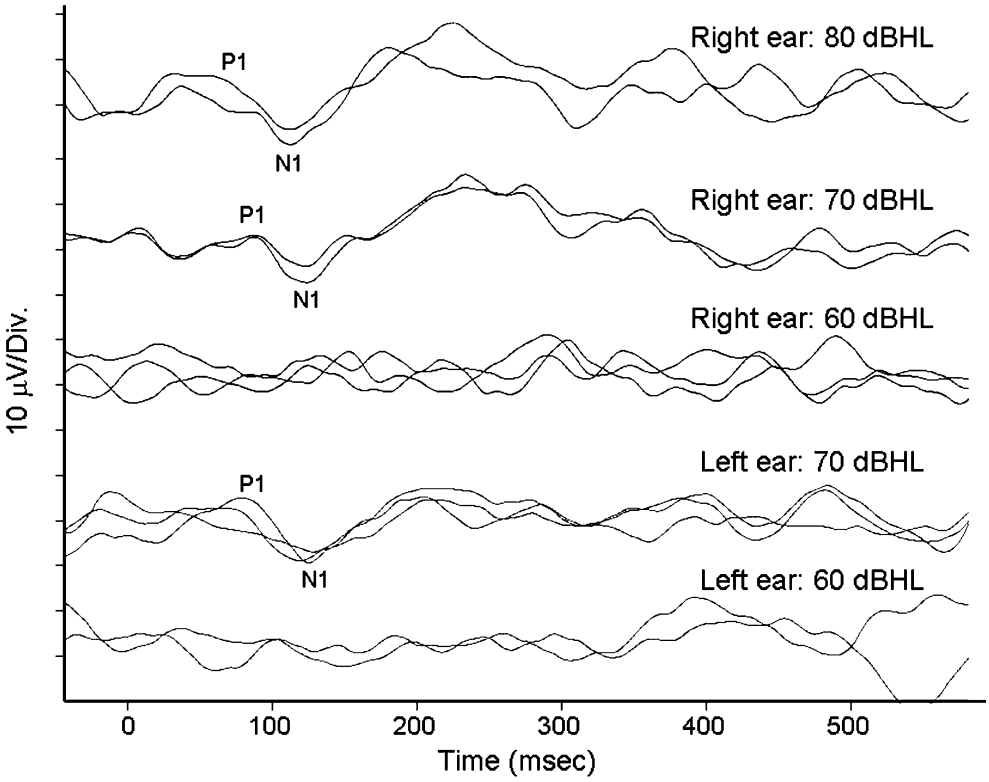

Figure 14–1.4. CAEPs to 500-Hz tone bursts presented to the left and right ears.

for, example, be expected to show a threshold decrease between assessments at 6 weeks and 18 months of up to 10 dB (particularly for low-frequency stimuli). See Chapter 9 for details.

When the child was tested at 12 years of age, 40-Hz ASSR and CAEP thresholds were obtained at similar levels. This result is consistent with recent studies comparing these tests in hearing-impaired adult subjects who have shown equivalent response thresholds (particularly to low-frequency [500-Hz] stimuli) (Tomlin, Rance, Graydon, & Tsialios, 2006; Van Maanen & Stapells, 2006). Maturation studies involving the CAEP and 40-Hz ASSR have in both cases suggested that the developmental course of the potential is not complete until adolescence (Pethe, Muhler, Siewert, & von Specht, 2004; Ponton, Egermont, Kwong, & Don, 2000). This child's auditory pathway, however, appeared (at the age of 12 years) mature enough to produce responses at levels close to hearing threshold.

The AEP findings for the multiply disabled child described in this study were "normal" or at least consistent with the degree of her hearing loss. That is, there was no suggestion that central factors had influenced the results. Because cerebral palsy is a motor disease, sensory responses such as the AEPs are expected to be unaffected. The impact of other forms of neurological compromise (which can affect the central auditory pathways)

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on the ASSR is yet to be fully explored and may need to be considered by clinicians in some circumstances.

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Case Study 2
An Infant with Sensorineural Hearing Loss Following Meningitis

Author: Gary Rance
Affiliation: University of Melbourne

Subject History

Subject M was born at 40 weeks post-conceptual age after an uneventful pregnancy. The neonatal course was normal, and the child's health was good until he suffered a bout of bacterial meningitis at 5 weeks of age. Subject M was born before the advent of newborn hearing screening in Australia, so no formal assessment of hearing acuity was made before his illness. His parents did, however, report rudimentary behavioural responses (e.g., stilling, aural palpebral reflex) to sound at levels consistent with normal hearing.

Results

Initial hearing testing took place at the University of Melbourne School of Audiology Clinic after discharge from hospital. At the time of testing, 18 days after