

Chapter 2

CLINICAL APPLICATION OF AUDITORY EVOKED POTENTIALS IN INFANTS: COMPARING THE AUDITORY BRAINSTEM RESPONSE AND AUDITORY STEADY STATE RESPONSE

This chapter aims to provide a theoretical background to the empirical research and provides a critical evaluation and interpretation of the relevant literature pertaining to the scope of this study

2.1 INTRODUCTION

'From the moment that Auditory Evoked Potentials (AEP) were first recorded, audiologists sought to exploit the responses in order to evaluate the hearing status of persons difficult to test' (Jerger, 1998: editorial). The use of AEP's for estimation of hearing sensitivity and infant hearing screening has had a major impact on the ability to identify hearing impairment in children, as this provides an objective means of assessing the integrity of the peripheral and central auditory systems (Stach, 1998:293). The Auditory Brainstem Response (ABR) has become the most widely clinically used AEP in estimating hearing thresholds, but for the past few decades an evoked potential, particularly suited for frequency-specific measurements, the Auditory Steady State Response (ASSR), has come under close scrutiny (Hood, 1998:117). In addition to estimating hearing sensitivity in infants, the ASSR promises to provide a better evaluation of hearing aid performance (Swanepoel, Schmulian & Hugo,

2002:52), which is an important component in the validation of hearing aid fittings.

This chapter therefore explores the clinical application of Auditory Evoked Potentials – comparing the ABR and ASSR as an objective procedure in the diagnosis of hearing loss and validation of hearing aid fitting in infants.

In the first section, the current procedures of choice for early intervention for infants will be discussed under the following two sub-headings: **Early identification and diagnosis of hearing loss** and **amplification for infants with hearing loss**. After laying this foundation, a critical discussion of **AEP's in pediatric audiology** will follow.

2.2 EARLY INTERVENTION FOR INFANTS WITH HEARING LOSS

Audiologists are entering a particularly optimistic era for the provision of early intervention services. There are technological advances resulting in much earlier identification of childhood hearing loss, improved amplification devices providing enhanced audibility, and increased opportunities for families to receive interventions that are responsive to family-identified needs (Moeller, 2001:109).

The Joint Committee on Infants Hearing (JCIH) therefore endorses early detection of and intervention for infants with hearing loss through integrated, interdisciplinary systems of universal hearing screening, evaluation, and family-centered intervention (Northern & Downs, 2002:269). This very early intervention maximizes the prospects that these patients will acquire the communication skills necessary to achieve their full potential (Kirkwood, 2002: editorial).

2.2.1 Early identification and diagnosis of hearing loss

Hearing loss is an important health problem in childhood that severely impacts on quality of life. The identification of permanent hearing impairment is the first step in a lifelong process for each infant (Seewald, 2000: vii). Early identification of hearing loss in children has always been a longstanding clinical priority in audiology, as hearing loss that goes undetected in infants and young children compromises optimal development and personal achievement (Diefendorf, 2002:469). Language and communication serve as a foundation for normal child development, and delays in the acquisition of these skills affect literacy, academic achievement, and social and personal development (Hayes & Northern, 1997:4). Identification of a child's hearing loss at an early age is therefore the first step in a comprehensive plan that allows for early medical management, consideration of acoustic amplification, and placement in an early intervention program (Diefendorf & Weber, 1994:43).

With the positive effect of early identification, the Joint Committee on Infant Hearing (2000) in the USA recommends that, whenever possible, diagnostic testing should be completed and habilitation should begin by the time an infant with a congenital hearing impairment reaches the age of six months. The effectiveness of the early intervention process hinges on the audiologist's ability to accurately predict hearing thresholds in the first months of life. The primary objective in assessing the hearing of an infant or young child is to obtain reliable, ear-specific and frequency-specific information on auditory function as soon after birth as possible (Bachmann & Hall, 1998:4). This objective can currently only be met through the use of auditory evoked potentials (AEP) (Sninger & Cone-Wesson, 2002:298).

AEP's have been used in diagnostic audiology for more than three decades and is becoming increasingly prominent as the age of hearing loss identification is being reduced significantly due to Universal Newborn Hearing Screening (UNHS) programs (Roeser, Valente & Hosford-Dunn, 2000:10).

The challenge of accurately determining the hearing status of an infant or young child is reliant on specialized training and extensive clinical experience (Hayes & Northern, 1997:234). No single auditory test is precise enough to be a perfect and complete assessment tool. Defining the nature and degree of an infant's hearing loss requires the use of multiple tests and techniques. The need for a test-battery approach in pediatric assessment can therefore not be overstated (Diefendorf, 2002:473). The basic pediatric hearing evaluation includes a thorough developmental history, followed by behavioral frequency-specific threshold tests, acoustic immittance measurements, otoacoustic emission tests (OAE) and ABR as necessary (Hayes & Northern, 1997:234). The pediatric hearing evaluation typically is an ongoing activity and should be adaptable to different circumstances (Hayes & Northern, 1997:234).

With the age of identification decreasing, behavioral conditioning of neonates and very young infants to sound field auditory stimuli is not feasible (Diefendorf & Weber, 1994:56). An acoustic immittance test battery can be used to categorize the nature of the hearing loss into conductive, cochlear, or brainstem pathology (Northern & Downs, 2002:211; Hayes & Northern, 1997:251). Although immittance can provide valuable information, it cannot predict the degree, configuration, type and symmetry of the hearing loss.

With the introduction of clinical devices in 1988 for measuring evoked otoacoustic emissions, this technique has become a relatively recent adjunct to nonbehavioral physiologic-based auditory response measurements (Hall, 2000:2). The presence of EOAE's has proven to be evidence of a normal functioning cochlea and peripheral hearing system. However, Robinette & Glatke (2000:506) cautions that OAE's cannot be used to estimate the amount of hearing loss. The application of OAE's include the screening for hearing loss in the newborn and pediatric population, augmenting behavioral test results in difficult-to-test patients, developing a true differential diagnosis in terms of separating hearing loss into "sensory" and "neural" components and identifying individuals with subtle abnormalities of CNS function (Robinette & Glatke, 2000:506).

In order to objectively measure the neural responses beyond the sensory response of the cochlea, AEP's must be employed. Mendel, Danhauer & Singh (1999:7) defines AEP's as electrical activity evoked by sounds arising from auditory portions of the peripheral or central nervous system traveling from cranial nerve VIII to the cortex – also known as auditory evoked responses (AER). Although inferences can be made about hearing from the evoked potential data, it should be emphasized that it is not a test of hearing, but rather a test of synchronous neural function – the ability of the central nervous system to respond to external stimulation in a synchronous manner (Hood, 1998:95).

The current most common classification of AEP according to the latency epoch of the response to be examined, was adapted from the work of Picton et al. in 1974 and 1977 and Picton and Fitzgerald in 1983 (Ferraro & Durrant, 1994:318). The *late latency response* (LLR) is the electrical potentials emanating from the surface of the scalp in response to an

auditory signal. These responses are generated by the cortex at time intervals of 100 to 200 msec after presentation of an auditory stimulus (Hood, 1998:4). These include the N1 complex and the P300 (Ferraro & Durrant, 1994:318). The *middle latency response* (MLR) occurs between 10 and 80 msec following signal onset and are thought to arise from thalamic and primary cortical projection areas (Hood, 1998:4). The most prominent of these is the 40 Hz steady state potential (SSP) (Ferraro & Durrant, 1994:318).

Those AEP's occurring within the first 10 -15 msec following stimulus onset are generally referred to as the "early" or *short latency responses* (SLR). The SLR includes the ABR and also several components preceding the ABR that are recorded via electrocochleography (ECoChG) (Burkard & Secor, 2002:233). Other SLR include the slow-negative potential (SN10) and the frequency following response (FFR). The clinical use of both these SLR's has been overshadowed by that of other AEP's like the ABR.

The late latency responses are present in infants and children, but are unreliable for threshold estimates in sleeping individuals and the recording and interpretation in children require considerable experience (Stapells, 2000a:13; Hall, 1992:107). The middle latency responses are not reliably obtained in infants and young children, and their absence in an otherwise normal sleeping infant may be completely normal (Stapells, 2000a:13).

The ABR has none of these limitations and has become the procedure of choice in the diagnostic assessment of the difficult-to-test populations (Stapells, 2002:14; Bachmann & Hall, 1998:41; Hall & Mueller, 1997:321). Several recording methods have been proposed in which the ABR can be used to predict the degree, configuration, type and symmetry of the

hearing loss (Hood, 1998:98). Many reports exist demonstrating the usefulness of these techniques in the diagnostic process of hearing loss in infants (Gorga, 2002:49; Stapells, 2000a:16; Gorga, 1999:31; Bachman & Hall, 1998:41; Stapells & Oates, 1997:261). The ASSR have recently gained considerable attention and caused excitement among audiologists, especially those involved in the assessment and subsequent hearing aid fitting of infants with hearing loss (Stapells et al., 2005:43).

2.2.2 Early amplification for infants with hearing loss

Once a hearing impairment has been identified, a complete assessment must be performed in a valid and timely manner. The findings from the assessment are used to develop the initial components of the intervention for the infant's entire life (Seewald, 2000: vii). Although many guidelines, such as the Joint Committee on Infant Hearing (JCIH, 2000:10), call for application of intervention procedures to begin no later than six months of age, the challenge of meeting such an obligation is daunting. The fitting of hearing aids on infants has always presented problems due to the limited capability to utilize standard behavioral testing techniques. With infants, hearing aids are fitted on the basis of only a few thresholds per ear, with no suprathreshold auditory perception (Pediatric Working Group, 1996:53). Even with the more recent advances in infant assessment, the threshold predictions are useful, but do not replace behavioral audiometry (Scollie & Seewald, 2002:687). The hearing aid selection, fitting, verification and validation process is therefore an ongoing challenge in this young population.

2.2.2.1 *Approaches to pediatric hearing aid fitting*

The immediate goal of sensory assistance to hearing impaired children is to provide as much sensory information as possible with regards to the sound patterns of speech (Boothroyd, 1997:17). The long term goal of enhancing sensory capacity is to increase the speed and quality of development of spoken language skills – to employ a *developmental* rather than *remedial* approach (Ross, 1996:13). Success in meeting this long-term goal depends not only on aided sensory capacity, but also on communicative experience, combined with appropriate clinical and educational management (Boothroyd, 1997:17).

Once hearing loss has been characterized, the next step is to determine whether amplification should be worn (Lewis, 2000:150). According to The Pediatric Working Group (1996:54), “thresholds equal to or poorer than 25 dB HL would indicate candidacy for amplification in some form.” As stated before, the goal of amplification is to ensure audibility of the speech input, verify that sounds are not uncomfortably loud and to ensure consistent audibility and hearing aid performance over time (Palmer, 2005:10; Kuk & Marcoux, 2002:504).

Although similar decisions about amplification characteristics must be made for the infant as for the adult, the information on which these decisions are based and the needs of these two groups are quite different (Palmer, 2005:11; Beauchine & Donaghy, 1996:145). At the simplest level, infants’ ears are smaller than those of adults: a difference that significantly impacts amplification-fitting decisions, such as choice of moulds and choice of prescriptive targets (Palmer, 2005:11; Scollie & Seewald,

2002:687; Dillon, 2001:410; Lewis, 2000:150; Beauchine & Donaghy, 1996:145).

Moreover, audiological information available at the time of hearing instrument fitting may be limited in the case of infants. The pediatric audiologist needs to rely on threshold estimates at the time when the hearing instruments are selected. Delaying amplification until complete audiological information is available, may mean that the infant is without amplification during critical periods of language development (Scollie & Seewald, 2002:685; Beauchine & Donaghy, 1996:145).

Furthermore, the communication needs of an infant who has a congenital hearing loss are also distinct from those of an adult who has progressive, late-onset hearing loss. Infants differ from adults in how they *use* amplification. They listen to speech from different distances and heights and amplification should account for these input differences. Infants also differ from adults in that they use amplification to *acquire* spoken language. They do not have the same knowledge base that adults have when attempting to make sense of auditory signals that may be distorted, incomplete, or affected by noise (Scollie & Seewald, 2002:685; Lewis, 2000:150; Beauchaine & Donaghy, 1996:145).

Pediatric amplification fitting procedures should therefore provide objective, valid, and reliable measures of hearing aid performance for speech-level and high-level inputs for the infant/child (Palmer, 2005:12; Scollie & Seewald, 2002:689, Dillon 2001:404). These measures should take into account the needs of infants and children for auditory self-monitoring and the acquisition of auditory processing abilities through aided sound.

The hearing aid fitting process for infants can be described as five sequential stages (Pediatric Amplification Protocol, 2003:15; Scollie & Seewald, 2002:685; Pediatric Working Group, 1996:53). These stages are summarized in Table 2.1.

Table 2.1 Stages of hearing aid fitting process

| Stage | Process |
|--|--|
| <ul style="list-style-type: none"> • Assessment | <ul style="list-style-type: none"> ➤ The hearing loss is measured, and candidacy for amplification is determined |
| <ul style="list-style-type: none"> • Selection | <ul style="list-style-type: none"> ➤ Numeric target for hearing aid electroacoustic performance are calculated, and appropriate hearing aids are chosen |
| <ul style="list-style-type: none"> • Verification | <ul style="list-style-type: none"> ➤ The hearing aids are adjusted to provide the desired electroacoustic performance |
| <ul style="list-style-type: none"> • Validation | <ul style="list-style-type: none"> ➤ Aided auditory function is evaluated and compared with habilitative goals |
| <ul style="list-style-type: none"> • Informational Counseling and follow-up | <ul style="list-style-type: none"> ➤ Orientation to hearing aids are provided and hearing aid usage is monitored |

A short discussion of each of these stages will follow:

- *Assessment*

The efficacy of hearing aid fitting is predicated on the validity of the audiological assessment. An essential goal of the comprehensive audiological assessment is to obtain ear- and frequency- specific estimates of hearing threshold for use as a starting point in hearing instrument fitting at the earliest opportunity (Roush, 2005:105; Pediatric Working Group, 1996:54). Complete audiological data is seldom obtained when testing the very young child. In the absence of an

audiogram, hearing aid fitting should proceed on the basis of frequency-specific ABR threshold estimations unless neurological status contra-indicates such action (Roush, 2005:105; Scollie & Seewald, 2002:689; Ross, 1996:16; Diefendorf, Reitz, Escobar & Wynne, 1996:125).

- *Selection*

The Pediatric Working Group (1996:54) recommended that infants/children with thresholds poorer than 25 dB HL between 1000 and 4000 Hz should be seen as candidates for amplification – either through the use of personal hearing aids or some other form of amplification (Lewis, 2000:150). Once the decision to provide amplification has been made, selection of hearing aids is a complex process (Scollie & Seewald, 2002:691; Beauchaine & Donaghy, 1996:145). Recent advancements in hearing instrument technology offer the potential for significant improvement in the language and communication abilities and overall quality of life of infants with hearing loss (Buerkli-Halevy & Checkley, 2000:77). It is important to select amplification based on the full range of unique characteristics of each infant, including the hearing loss, the family, the educational and home environment, and available hearing aid technology (Buerkli-Halevy & Checkley, 2000:77; Beauchaine & Donaghy, 1996:145).

- *Verification*

In the context of early intervention, infants will wear their hearing aids at fixed, clinician-determined settings for a long period of time (Scollie, 2005:91). Recent consensus statements have recommended that hearing aid prescription should be done in an *objective* manner

(Pediatric Working Group, 1996; Pediatric Amplification Protocol, 2003). At the verification stage, objective hearing aid prescriptions are used to prescribe specific amplification characteristics (Scollie, 2005:91). The hearing aids are adjusted until they provide the electroacoustic performance that is deemed appropriate for each infant/child (Scollie & Seewald, 2002:698; Beauchaine, 2002:106). The output of the instrument is measured objectively across frequency and input ranges. This procedure must confirm that the real-ear performance of the instrument provides output levels that are comfortable, safe, and without feedback. The use of this objective approach results in consistent treatment across infants and children (Scollie, 2005:91).

- *Validation*

Once the prescriptive procedure is complete, and the settings of the hearing aids have been verified, the validation process begins (Pediatric Amplification Protocol, 2003:15). Validation of aided auditory function is a critical component of the pediatric amplification provision process. The purpose of validating aided auditory function is to demonstrate the benefits/limitations of an infant's/child's aided listening abilities for perceiving speech of others as well as his/her own speech (Pediatric Amplification Protocol, 2003:15; Dillon, 2001:106; The Pediatric Working Group, 1996:56). Validation is accomplished, over time, using information derived through the aural habilitation process, as well as the direct measurement of the infant's/child's aided auditory performance.

- *Informational counseling and follow-up*

Thorough and suitable counseling, monitoring and follow-up are essential in a pediatric hearing aid fitting process. Hearing aid orientation programs should include all members who will be assisting the infant (Beauchaine, 2002:111). Typical audiological follow-up schedules for infants and young children are at least every three months to the age of three years. More frequent visits may be required when fitting infants younger than six months of age, (Beauchaine, 2002:111).

In the past audiologists have relied on aided audiograms (also known as functional gain measurements) as the primary **verification** tool for hearing aid fittings in infants and young children (Stelmachowicz, Hoover, Lewis & Brenman, 2002:38; Seewald, Moodie, Sinclair & Cornelisse, 1996:165; Hedley-Williams, Thorpe & Bess, 1996:107). Technically, functional gain is defined as the difference in dB between aided and unaided sound-field thresholds as a function of frequency. (Stelmachowicz et al., 2002:38). Typically, the goal has been to “shift” thresholds into the range of 20-25 dBHL

Over the years, it has been acknowledged that several limitations are associated with the use of functional gain approaches for hearing aid **verification** (Seewald, Moodie, Sinclair & Cornelisse, 1996:178).

One serious limitation of this procedure is related to the form in which the performance criteria are specified (Stelmachowicz et al., 2002:38; Seewald et al., 1996:178). When a purely audiometric-based approach is taken to the selection process, it is not possible to verify that the desired

electroacoustic characteristics have been provided to the infant without valid behavioral test results. Consequently, for infants, this approach will be of limited use when important selection-related decisions need to be made (Pediatric Amplification Protocol, 2003:13; Dillon, 2001:106). Another criticism of this procedure is the poor test-retest reliability (Stelmachowicz et al., 2002:13).

Functional gain measurements indicate only the frequency/gain characteristics of a hearing aid (Seewald et al., 1996:178). There are additional electroacoustic characteristics of hearing aids that should be considered within the selection process. Consideration should be given to aspects such as output limiting, compression thresholds, compression ratios and cross-over frequencies. Functional gain also does not supply frequency specific information. It gives information across the frequency spectrum at octave frequencies, but the inter octave frequencies and troughs are overlooked. The frequency resolution is therefore poor (Dillon, 2001:106). Small changes in electro-acoustic output of the hearing aid, or acoustic modifications may create alterations in the frequency response and gain characteristics of the hearing aid. This will not necessarily be noted in the functional gain measurement.

Aided audiograms describe hearing aid function for very soft sounds only, and then only at a few frequencies. In cases of severe to profound hearing loss, minimal or mild loss, or when non-linear signal processing, digital noise reduction, or automatic feedback reduction circuitry is used, misleading information may be obtained (Scollie & Seewald, 2002:688).

Due to the above limitations, computerized real-ear probe microphone measurements have become the preferred procedure to fit and adjust

hearing aids with infants. But functional gain measures do however play a role in the ongoing process of **validation**. Dillon (2001:419) emphasizes that these measurements should be a supplement to the electroacoustic measurements. Functional gain measures have the following uses:

- It demonstrates to the parents that the child is capable of reacting to sound (Dillon, 2001:419). Aided and unaided speech reception or speech awareness thresholds can demonstrate the benefit of amplification to parents of infants. It may also rule out the possibility of non-organic hearing loss, neurological conditions, or auditory neuropathy (Stelmachowicz et al., 2002:39).
- It demonstrates that the hearing aid maximum output exceeds the child's hearing threshold at each frequency tested (Dillon, 2001:419).
- An aided threshold at the level expected, given the hearing aid coupler gain and unaided hearing threshold, provides further confirmation of the child's unaided thresholds (Dillon, 2001:419).
- In the case of profound hearing loss, aided thresholds at the expected levels confirm that the unaided thresholds were not based solely on vibratory sensations (Dillon, 2001:419). Aided thresholds are also the best way to document performance for bone-conduction instruments, frequency-transposition devices and cochlear implants (Stelmachowicz et al., 2002:42).

Validation of aided auditory function is a demonstration of the benefits and limitations of aided hearing abilities and begins immediately after the fitting and objective electroacoustic verification of amplification (Pediatric Amplification Protocol, 2003:15). Validation is an ongoing process designed to ensure that the child is receiving optimal speech

input from others and that his or her own speech is adequately perceived (Pediatric Working Group, 1996:56; Pediatric Amplification Protocol, 2003:14). Functional gain is measured by finding the hearing thresholds in a sound field while a person is unaided and again while aided – through the use of behavioral audiometric procedures (Dillon, 2001:106).

Infants are however unable to provide conclusive behavioral information. It may therefore be necessary to incorporate subjective non-traditional evaluations, such as parent questionnaires, to gain behavioral information about the fitting outcome (Scollie & Seewald, 2002:701). Without the data derived from behavioral assessments, it is difficult to assess the performance of hearing aids even when the theoretical amplification specification is known (Gamham et al., 2000:267). Objective measures – using AEP's - to assess hearing aid performance would potentially aid the management of these difficult-to-test subjects as the behavioral functional gain measurements may only be performed after the infant has reached an appropriate developmental age where a response such as the head turn response may be utilized to measure functional gain. Therefore AEP's may provide useful information when behavioral functional gain measurements are not readily available due to the subject's age or developmental incapacity. The next section will therefore focus on AEP's in the field of pediatric audiology.

2.3 CRITICAL EVALUATION OF AEP's IN PEDIATRIC AUDIOLOGY

There has always been a need for objective tests that assess auditory function in infants, young children and/or any patient whose developmental level precluded the use of behavioral audiometric techniques. Although several approaches have been tried, for the past 25

years, that need has been met primarily by the measurements of short-latency auditory-evoked potentials, primarily the auditory brainstem response (ABR) (Gorga & Neely, 2002:49). In recent years the Auditory Steady State Responses has become available as a different technique to measuring the brain's responses to sound (Picton et al., 2002:65). In pediatric audiological practice AEP's have proven to be indispensable for diagnostic purposes but they have also begun to demonstrate the potential to assist beyond the diagnostic process with the validation of amplification.

In the following section these two techniques will be discussed in terms of their application in the field of pediatric audiology, both diagnostic and in amplification validation.

2.3.1 Auditory Brainstem Response

The ABR is mostly used in the assessment of auditory function in infants, children and adults who cannot participate in voluntary audiometry and is by far the most widely used AEP in audiology (Arnold 2000:451; Hood, 1998:96). The popularity of the ABR stems from the fact that it is a robust response that varies very little between individuals (including infants), making the response fairly easy to identify under most circumstances (Hall, 1992:20). It is also highly stable – characteristics of the response do not vary between wakefulness and sleep and are not affected by most medications, which mean that children may be tested reliably during natural or sedation induced sleep (Arnold, 2000:455; Rance et al., 1995:499). These characteristics have made it the most commonly used electrophysiological tool to estimate hearing thresholds in difficult-to-test populations. The ABR will be discussed in terms of three applications in the

field of pediatric audiology, namely: **detection, diagnosis and hearing aid fitting in infants.**

2.3.1.1 Detection of hearing loss

Screening, or early detection, of disorders has received increasing attention in health care over the last quarter century (Feightner, 1992:1). The general premise for screening, or early detection, clearly makes sense. Early detection offers the opportunity to recognize the condition before symptoms appear, and to prevent or diminish suffering (Feightner, 1992:2). Hearing loss is an invisible disability and is nearly impossible to detect during a routine clinical examination. Thus, if hearing loss is not detected through newborn hearing screening programs, it often goes undetected before 18 months of age (Diefendorf, 2002:469; Hayes & Northern, 1997:214).

Although the ABR is not a direct test of hearing sensitivity, it has earned a strong clinical reputation as a valuable tool to evaluate the integrity of the auditory pathways (Diefendorf, 2002:471; Stapells, 2000a:13). Click evoked ABR's can be recorded from infants as young as 27 weeks gestation age, although responses may be poorly formed (Hall, 1992:490). By 33 to 35 weeks of gestation, responses are more stable, and visual detection level is comparable to that of older infants. Traditional ABR screening depended on identification of wave V at 30-40 dBnHL (Northern & Downs, 2002:285).

Automated ABR (AABR) systems have been developed and used specifically for hearing screening purposes. The automated ABR systems use a rule-directed, statistical method to detect a response – thus

eliminating subjective response recognition (Cone-Wesson, 2003:266). These automatic detection algorithms works by comparing the online responses from the infant with a 'normal' template response pattern obtained from a large sample population of newborns. If the test infant's responses correlate with the normative data, the automated instrument renders a 'pass' decision. If there is no correlation between the 'normal' template and the test infant's responses, a 'refer' response is obtained – suggesting the need for further testing (Northern & Downs, 2002:285). These ABR systems are entirely objective and are programmed to determine pass or refer criteria for infants younger than six months of age.

A click stimulus is used when eliciting an ABR. The click ABR accurately approximates behavioral pure tone thresholds in the middle to high frequency regions (Sninger & Cone-Wesson, 2002:303) – therefore limiting detection of hearing loss in different frequency ranges (Stapells, Gravel & Martin, 1995:361). Information from this single intensity screening test is insufficient to predict degree of hearing impairment or the site of dysfunction (Hayes & Northern, 1997:256). The advantages and limitations of the click evoked ABR will be discussed in detail in the following section.

2.3.1.2 Diagnosis of hearing loss

i. ABR threshold evaluations using clicks

The most widely used evoked potential method for evaluating auditory threshold is the ABR to non-masked broadband clicks (Stapells & Oates, 1997:258). The click-evoked ABR consists of a series of seven positive-to-negative waves, occurring within about 10 ms after stimulus onset (Arnold, 2000:451). It was not until the late 1960's that electrical potentials

generated by the brainstem were identified in the laboratories of Jewett and colleagues in the USA and Sohmer and Feinmesser in Israel (Hall & Mueller, 1997:322; Hood, 1998:5). Jewett and colleagues demonstrated that neural responses could be recorded from the brainstem pathways – showing a response composed of a series of five to seven peaks (Burkard & Décor, 2002:233). It is generally agreed that the ABR is generated by the auditory nerve and subsequent fiber tracts and nuclei within the auditory brainstem pathways. A series of Roman numerals (from I to VII) were assigned to the peaks. These designators have been used since that time to identify the various components of the ABR (Hood, 1998:5). The most widely used ABR measure is the latency of a component peak (Don & Kwong, 2002:274).

The click-evoked ABR yields the clearest ABR response for threshold estimation as this robust response varies little between individuals and is easy to identify (Hall, 1992:20; Arnold, 2000:455). In assessing hearing sensitivity, wave V of the ABR is used because it is the most robust of the waves and the one best correlated with behavioral audiometric thresholds (Arnold, 2000:456). The lowest click level at which Wave V can be elicited provides information about the degree of hearing loss (Arnold, 2000:456).

However, the rapid onset of the click, and its broad frequency spectral content, results in activation of a wide area of the basilar membrane. Since a broad range of frequencies is stimulated, it is not possible to obtain accurate information about hearing sensitivity at different frequencies using a non-masked click alone (Stapells & Oates, 1997:248). When using frequency-specific stimuli, there is a trade-off between frequency specificity and neural synchrony (Hood, 1998:96; Hall 1992:123).

The acoustic principle underlying this trade-off, involves the relationship between the duration of the stimulus and its frequency content – the longer the duration, the more frequency specific it will be.

Another aspect influencing the frequency specificity of the click ABR is the transducer. A 100-microsecond electrical pulse, impressed on a standard earphone, generates a broadband signal (click) whose primary frequency emphasis is determined by the resonant frequency of the transducer (Hood, 1998:96; Hall, 1992:123). Thus a click, though a broadband stimulus, is nonetheless somewhat frequency specific, based primarily on the frequency response of the earphones (Gorga, 1999:31; Hood, 1998:96). A click therefore, with its abrupt onset and brief duration, is better to elicit a synchronous neural response, but is not very frequency specific (Hood, 1998:97). The maximum energy peaks are in the frequency region between 1000 and 4000 Hz (Hood, 1998:96; Hall, 1992:107). The greatest agreement with pure-tone thresholds is in the 2000 to 4000 Hz frequency range. Click ABR's do; however, provide a gross estimate of hearing sensitivity and an assessment of VIIIth nerve and auditory brainstem pathway integrity – allowing the clinician to rule out possible neurological involvement (Arnold, 2000:454; Gorga, 1999:31; Stapells & Oates, 1997:248).

Stapells & Oates (1997:258) cautions that this may be true, on average and across a large group of patients with hearing loss. It does not translate into one being able to use the click ABR threshold as a reliable estimate of 2000-4000 Hz threshold for *individual* patients. These researchers have demonstrated that any particular click ABR threshold may represent a wide range of pure-tone thresholds, making accurate determination of

degree of hearing loss impossible. This seems especially true in the case of sloping hearing losses.

The major explanation for the problems with the click ABR for threshold estimation lies with the broad-band nature of clicks, and the resulting frequency contributions to the click-evoked ABR (Stapells & Oates, 1997:261). A normal click ABR threshold does not necessarily imply normal hearing. It may only imply an area of normal sensitivity between 1000 and 4000 Hz (Perez-Abalo et al., 2001:200; Rickards et al., 1994:327). When a hearing impairment is restricted to a particular frequency region, click-evoked ABR will often miss the loss or substantially underestimate the degree of the loss (Stapells, 2000a:15; Stapells, Gravel & Martin, 1995:361). This situation can occur with high frequency losses, low-frequency losses or impairments confined to the mid-frequency regions (e.g. 'cookie-bite' losses) (Stapells & Oates, 1997:261). As in behavioral audiometry in older children, narrower band stimuli must be used in order to obtain ABR threshold estimated for specific frequency regions. In contrast to thresholds to clicks, ABR thresholds to brief tonal stimuli provide more frequency specific results.

ii. ABR threshold evaluation using brief tones

The click-evoked ABR may be useful and clinically practical for estimation of auditory function in the 1000 – 4000 Hz region. This might be adequate for hearing screening, but information on auditory sensitivity across the audiometric range, especially the speech frequency region (500 – 4000 Hz) is essential for audiological management, such as for the fitting of hearing aids (Gorga & Neely, 2002:50; Hall, 1992:107). The ABR to clicks alone can therefore not provide information concerning hearing sensitivity

for specific frequencies (Gorga, 1999:31; Stapells, Gravel & Martin, 1995:361). Stapells, Gravel and Martin (1995:361) also state that hearing loss restricted to particular frequency regions may be underestimated or missed entirely by the click-ABR threshold. It is therefore not possible to characterize the shape of the hearing loss from click-evoked ABR alone even with consideration of the latency/intensity function (Sninger & Cone-Wesson, 2002:303). An estimation of low frequency hearing status is especially desirable in order to estimate auditory function across the audiometric range (Hall, 1992:107). Several types of stimuli and recording methods have therefore been proposed to provide information for narrower frequency regions, such as tone bursts, filtered clicks, tone bursts and clicks mixed with various types of noise, and high-pass masking of clicks (Hood, 1998:98). These techniques all have advantages and limitations. Tone burst stimuli are now widely available on commercial ABR instrumentation, and are therefore the most commonly used type of frequency specific stimuli in ABR testing (Hood, 1998:98; Stapells & Oates, 1997:258).

In attempting to approximate the behavioral pure tone audiogram, it has become fairly common to include brief-duration tonal stimuli as part of the test protocol in order to estimate the audiogram of young infants (Sninger & Cone-Wesson, 2002:303; Stapells, 2002:11; Hood, 1998:96; Hall & Mueller, 1997:360). This type of stimulus is the result of an attempt to find the “best compromise” that would maximize frequency specificity and neural synchrony (Hood, 1998:98). These stimuli have narrower frequency spectra than clicks but are substantially broader than the pure tone stimuli used for conventional audiometry, because of the brief rise/fall time (Hall, 1992:108).

Brief tone bursts have their concentration of energy at a nominal frequency of the tone (predominant energy peak) and sidebands of energy at lower and higher frequencies (Arnold, 2000:459; Oates & Stapells, 1998:62). The spread of stimulus energy to frequencies other than the nominal frequency is known as spectral splatter. Because the sidebands are less intense than the peak of energy, the frequency spread is more of a problem at high levels of stimulation (Arnold, 2000:459). The degree of spectral splatter is also influenced by several parameters of the stimuli, including rise time, duration, temporal shaping and type of transducer used (Oates & Stapells, 1998:62).

Various ramping or envelope shaping techniques such as Blackman ramping have been implemented as a way to improve frequency specificity of toneburst stimuli. At high stimulus intensities, stimulation can however still spread to adjacent frequency areas in persons with better hearing, due to basilar membrane mechanics (Arnold, 2000:459). An alternative way to ensure frequency specificity is to combine different masking methods with the stimuli (Gorga, 1999:29). The *notched noise* is currently the most clinically used masking technique (Arnold, 2000:459). Notched noise is similar to wide band noise, containing energy across the frequency spectrum, except within a certain narrow range of frequencies (the notch). The frequency, at which the notch occurs, corresponds to the frequency of the tone burst. Thus, the side bands of energy present in the tone burst are masked out, restricting the area of stimulation to the nominal frequency of the tone burst. This ensures that the ABR is generated by neurons sensitive only to the test frequency (Arnold, 2000:459; Gorga, 1999:36; Oates & Stapells, 1998:62).

Gorga (1999:40) concluded in his research, that accurate estimates of thresholds are possible for a wide range of frequencies, using tone burst stimuli. Reasonably accurate estimates of the pure tone behavioral audiogram from 500 Hz – 4000 Hz can be provided. Although a recent meta-analysis of the tone burst ABR literature by Stapells (2000b:74) has shown that across studies, tone-ABR thresholds have been found to be between 10 and 20 dBnHL in normal hearing individuals and are generally within 15 dB of behavioral threshold for hearing impaired individuals, some studies have questioned the frequency specificity and reliability of threshold estimation with low frequency tone-evoked ABR (Vander Werff et al., 2002:228; Dimitrijevic et al., 2002:206). The credence is that the ABR to 500 Hz tonal stimuli is *primarily* generated from the basal end of the cochlea, especially to higher-intensity stimuli, and thus these thresholds are poor predictors of low-frequency behavioral thresholds (Stapells & Oates, 1997:261).

Furthermore, ABR to both click and tone burst stimuli does not appear to be able to distinguish severe-to-profound hearing losses in the range of 85 to 95 dB HL from those in the more profound ranges of 100 to 120 dB HL (Stapells, 2000a:24). The possibility of residual hearing at these profound levels can therefore not be investigated through the use of ABR (Arnold, 2000:454; Rance, 1998:506). Another limitation of the ABR is the subjective nature of interpreting the results (Oates & Stapells, 1998:67; Bachmann & Hall, 1998:42). Interpreting ABR waves – especially to low frequency tone burst stimuli - is problematic. Interpretation of these results requires experience and expertise (Stapells, 2000a:13). These techniques may also be time consuming (Dimitrijevic et al., 2002:206).

In carrying out clinical ABR tests on infants and young children, clinicians usually proceed with an expectation that the patient will wake up at any moment (Stapells, 2002:26). The aim in pediatric audiology is therefore to gain as much information as possible in the time available. ABR test protocols, therefore aim to gather frequency-specific threshold information in the shortest possible time (Stapells, 2000a:26; Arnold, 2000:460). The duration of an ABR test session for infants and young children is determined by the amount of time they will remain asleep (Stapells, 2002:16). It is therefore essential to use a test protocol that is fast, efficient, and one that provides the greatest increase in clinical information with each successive step (Stapells, 2002:14). Although the click ABR provides important information about auditory function, it does not provide sufficient information to understand auditory function across the frequency range (Gorga, 1999:40). With low frequency information, provided through tone burst ABR, auditory function can be defined with greater precision. Acquisition of the high frequency information provided by the click ABR or 2000 Hz tone burst, in combination with low frequency information provided by the tone burst ABR, is necessary to define the configuration of the hearing loss (Arnold, 2000:461). This information is essential in the development of a habilitative program, including the use of personal amplification (Gorga, 1999:40).

2.3.1.3 The ABR in pediatric hearing aid fittings

Without the information from behavioral evaluations, it is difficult to assess the performance of hearing aids – even when the theoretical amplification specifications are known (Garnham, Cope, Durst, McCormick & Mason, 2000:267). Using electrophysiological measures to assist in the hearing aid fitting in infants is not a new idea. According to

Mahoney (1985:351) altered auditory evoked potentials were measured by Rapin and Graziani in 1967 under amplification. This procedure involved the adjustment of the hearing aid until the latency of wave V of the ABR decreased to within normal limits (Picton et al., 1998:315).

Some studies have used the *ABR threshold method*. According to Mahoney (1985:357), Mokotoff and Krebs (1976) obtained unaided and aided ABR thresholds, audiometric thresholds and electroacoustic measures on cooperative adult hearing aid users and found favorable correlations between these procedures. Other studies (Cox & Metz, 1980; Hecox, 1983) mentioned in Mahoney (1985:359), suggested the use of *ABR wave V absolute latency* and/or L-I slope to predict appropriate hearing aid specifications. The basic premises were that normal wave V latencies require an intact auditory system up to the neural generator, that normal L-I slope suggests normal dynamic loudness function and that speech intelligibility and ABR latency are correlated. It followed that if a hearing aid can be adjusted in gain, output, and compression characteristics to generate as normal an ABR as possible in a pathological ear, the procedure had merit as a tool for the evaluation of amplification. Another ABR Hearing Aid Evaluation method was employed by Kiessling (1982) (Mahoney, 1985:361). An unaided ABR projection system based on normal and *pathological amplitude growth*, to prescribe appropriate hearing aid gain, compression ratio and compression onset was used.

More recently Garnham et al. (2000:267) used the ABR as an objective measure to verify the aided hearing thresholds in a group of children. Objective data were collected from the ABR and behavioral thresholds were measured by use of age appropriate tests. When comparing the unaided ABR click thresholds to behavioral thresholds, the ABR threshold

was on average 9 dB lower. Using the same comparison for aided responses, a difference of <5 dB was observed. This group of researchers concluded that aided ABR thresholds are valuable in the management of young children. However, when performing these measurements, it is essential to be aware of the limitations of the hearing aid and the stimulus.

Although Mahoney (1985:356) illustrated the feasibility of using ABR for functional gain measurements, the widespread use of this technique did not occur. This procedure is technically challenging due to four main concerns. First, the click stimulus is very brief and can be significantly distorted both in the sound field speaker and in the hearing aid. The resultant stimulus artifacts may obscure interpretation of the responses (Garnham et al., 2000:268). Second, the most significant limitation concerning this technique stems from the fact that hearing aids react differently to rapidly changing stimuli than to more continuous stimuli which leads to distortion of the stimulus (Mahoney, 1985:368). Third, the click ABR is mainly related to high frequency gain and correlation between wave V latency and loudness is low, particularly when there is a sloping hearing loss (Picton et al., 1998:316). Fourth, the brief stimuli that are optimal for ABR recordings may not activate the hearing instrument's compression circuitry in the same way as longer-duration speech sounds (Brown, Klein & Snydee, 1999:196) and may be treated as 'noise' by hearing instruments with speech detection algorithms (Alcantra, Moore, Kuhnel & Launer, 2003:40). For these reasons attempts to use the ABR to evaluate hearing instruments have largely been abandoned (Purdy, Katsch, Dillon, Storey, Sharma & Agung, 2005:116).

2.3.1.4 *Summary of the ABR application in pediatric audiology*

As a conclusion to this critical evaluation of the ABR, Table 2.2 summarizes the advantages and limitations of the ABR.

Table 2.2 Advantages and limitations of the ABR

| Advantages | Limitations |
|---|--|
| Diagnosis | |
| <ul style="list-style-type: none"> • A noninvasive, safe approach • Stable response – resistant to state of consciousness • Characteristics similar between people – easy to identify response – even in infants • Recordable – close to behavioral thresholds • Tone burst stimuli can be used to provide more frequency-specific information | <ul style="list-style-type: none"> • Click ABR provides general assessment of high frequencies • No distinction between severe and profound losses • Stimuli contain energy over range of frequencies and may evoke a response at any of these • Time-consuming • Subjective interpretation of results |
| Validation Process | |
| <ul style="list-style-type: none"> • Potential to provide objective information concerning hearing aid functional benefit | <ul style="list-style-type: none"> • Click stimuli is very brief and distorts in speaker and/or hearing aid • Hearing aids react differently to rapidly changing stimuli • Click ABR is mainly related to high frequency gain and correlation between wave V latency and loudness is low • Compression circuitry activated differently from speech stimuli |

One technique that has demonstrated promise in addressing the limitations of the ABR in validating hearing aid fittings in infants is the Auditory Steady State Response (ASSR). This procedure also demonstrates promise in addressing some of the ABR limitations in assessing hearing abilities in the difficult-to-test population (Swanepoel, Hugo & Roode, 2004:531).

2.3.2 Perspectives on the Auditory Steady State Response

In the past two decades, an evoked potential particularly suited to frequency-specific measurement, commonly referred to as the Auditory Steady State Response (ASSR) or Steady State Evoked Potential (SSEP), has been under close scrutiny for clinical application (Perez-Abalo et al., 2001:200).

2.3.2.1 Definition and Development of Auditory Steady State Response

The ASSR are periodic scalp potentials that arise in response to regularly varying stimuli such as sinusoidal amplitude and/or frequency modulated tone (Rance, Dowell, Rickards, Beer & Clark, 1998:49). It yields a waveform closely following the time course of the stimulus modulation and a response specific to the frequency of the carrier. By varying the intensity of the eliciting stimulus a threshold response can be measured (Jerger, 1998: editorial).

The principle underlying the ASSR is based on the following cochlear mechanics as outlined by Lins, Picton, Boucher, Durieux-Smith, Champagne, Moran, Perez-Abalo, Martin and Savio (1996:84) and

illustrated by Figure 2.1: Sound waves produce an effect of polarization and depolarization of the inner hair cells. Only the depolarization of inner hair cells causes auditory nerve fibers to transmit action potentials. The electrical action potential output of the cochlea therefore contains a rectified version of the acoustic stimuli. This rectification causes the output of the cochlea to have a spectral component at the frequency at which the carrier was modulated. This component, which is not present in the spectrum of the stimuli, can be used to assess the response of the cochlea to the frequency of the carrier tone.

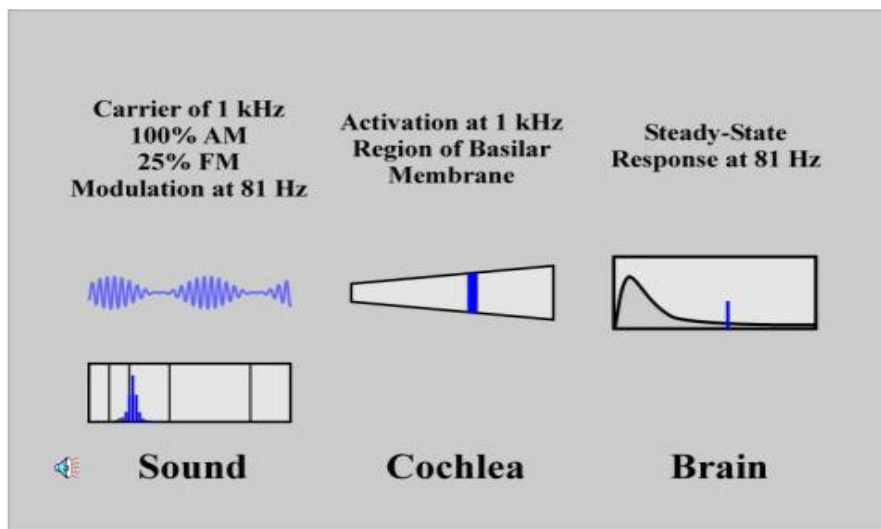


Figure 2.1 Principles underlying the ASSR (from Picton, 2005: conference presentation)

The stimuli used to evoke the ASSR are a modulated tone in the standard audiometric range (Cone-Wesson, 2003:267). The tone can be amplitude (AM) or frequency (FM) modulated; or both amplitude and frequency modulated. The stimuli consists of a carrier frequency (CF) (test frequency), modulated over time in the amplitude domain at a frequency of modulation (MF) (Perez-Abalo, et al., 2001:201). Figure 2.2 demonstrates the modulation of a pure tone.

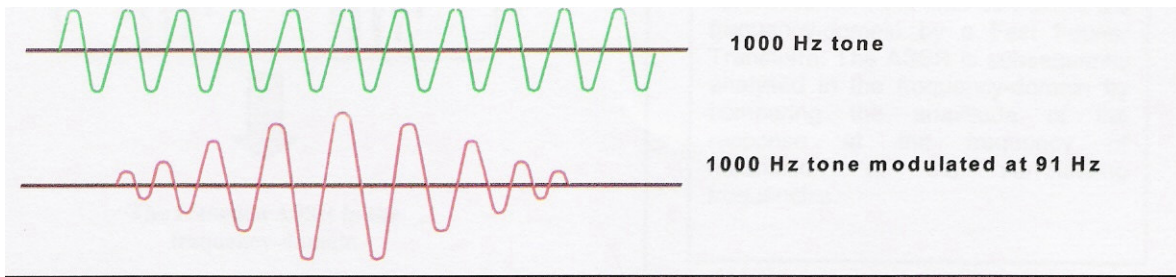


Figure 2.2 A single tone and a modulated tone (from Swanepoel, Schmulian & Hugo, 2002:51).

According to Dimitrijevic et al. (2002:206), ASSR's were first suggested as an objective means to assess hearing by Galambos and colleagues in 1981. These researchers used modulation frequencies between 35 and 55 Hz to assess hearing threshold. They subsequently showed that the 40-Hz steady-state response was easy to identify at intensities just above behavioral thresholds. However, some limitations for objective audiometry are present with the 40-Hz steady-state response such as: (1) The response is unreliable in estimating thresholds in infants and young children (Herdman & Stapells, 2001:41); (2) The response diminishes when subjects are asleep or sedated (Dimitrijevic, 2002:206 & Rance, 1995:500); (3) Response amplitude diminishes when several stimuli are presented simultaneously (John, 1998:59).

Recent work has therefore focused on alternative rates of stimulation for audiometric purposes. Some researchers have found that responses are recorded consistently – during sleep, and at low sound pressure levels - in all subjects (including infants) when a modulation rate of above 70 Hz is used (Stapells & Herdmann 2001:41; Lins et al., 1996:82; Rance et al., 1995:500; Rickards et al., 1994:327). Therefore the ASSR elicited by carrier frequencies with higher modulation rates have been proposed as an alternative to objective frequency specific audiometry (Perez-Abalo et al., 2001:200). The carrier sine wave is the frequency being tested and can be

presented at any low or high frequency tone as in pure tone testing (Swanepoel, Schmulian & Hugo, 2002:51). These modulated tones are as frequency specific as pure tones because spectral energy is contained only at the frequency of the carrier tone and the frequency of modulation (Cone-Wesson & Sninger, 2002:311; Hood, 1998:117).

Studies investigating the neural sources of the ASSR indicate they originate primarily from brainstem structures (Stapells, 2005:44; Kuwada et al., 2002:202) but this depends on the rate of modulation and subject state (Cone-Wesson, 2003:267). Although not yet confirmed, it is possible that the ASSR are ABR wave V to rapidly presented stimuli (Stapells, 2005:44). The ASSR is generated when the carrier frequency (test frequency) is presented at a rate (modulation frequency) that is sufficient to cause an overlapping of transient responses, thus being a sustained response (Swanepoel, Schmulian & Hugo, 2002:51). A carrier frequency stimulus triggers a specific region of the basilar membrane, activating hair cells in the cochlea in the region that corresponds primarily to the tone frequency. As the resulting neural activity travels along the auditory pathway, EEG activity 'synchronizes with' or 'follows' the amplitude modulation frequency (Lins et al., 1996:85). This means that the carrier frequency stimulates the cochlea with pockets of energy at the rate of the modulation frequency (Swanepoel, Schmulian & Hugo, 2002:51). The energy in the resultant response is at the frequency of modulation and its harmonics, allowing analysis of the response in the frequency domain (Herdman & Stapells, 2001:41).

The ASSR is recorded in a time-domain and must be converted to a frequency-domain by a Fast Fourier Transform (FFT) for analysis (Lins, 1996:85). In the frequency domain, the response to the carrier frequency

can be assessed by the amplitude and phase of the FFT component corresponding to the frequency of modulation of the carrier (Swanepoel, Schmulian & Hugo, 2002:51). Combining responses whilst maintaining both phase and amplitude information obtain an average response (Perez-Abalo et al., 2001:201). Figure 2.3 illustrates this procedure.

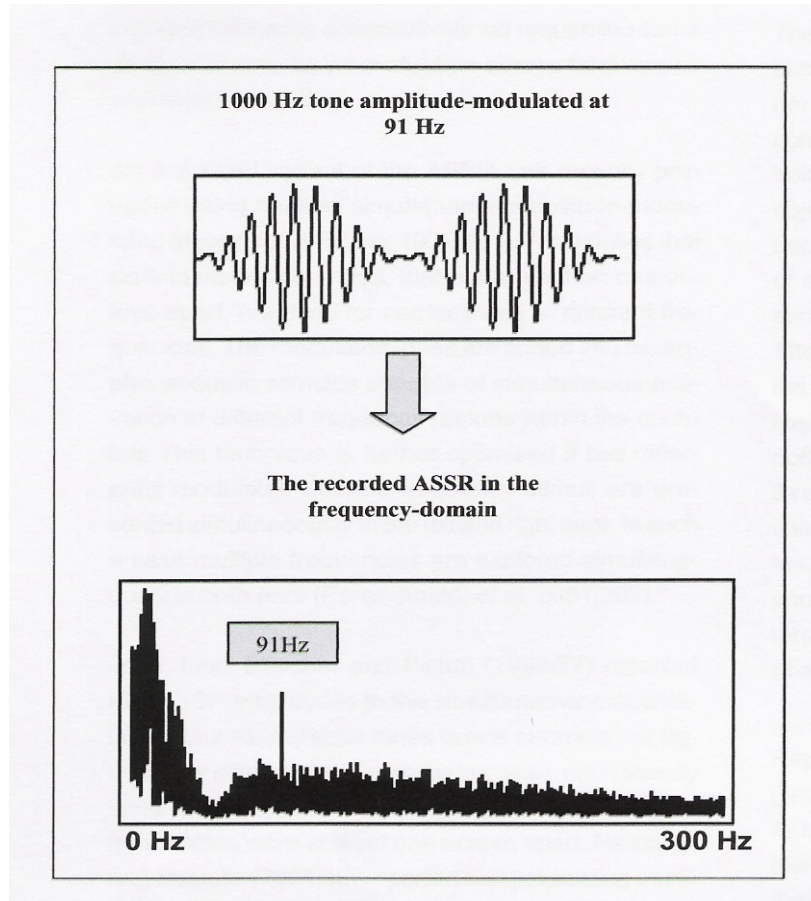


Figure 2.3 Recording the ASSR (from Swanepoel, Schmulian & Hugo, 2002:52).

i. Single stimuli vs. multiple stimuli ASSR

The ASSR can be evoked using a single frequency stimulus (Rance et al., 1995:501) or the ASSR can be evoked using multiple-frequency stimuli presented simultaneously (Lins et al., 1996:81). With the latter technique, it is possible to present multiple amplitude-modulated CFs simultaneously and perform a separate analysis for each MF used in the complex stimulus

(Sninger & Cone-Wesson, 2002:313). Lins and Picton (1995:420) showed that it is possible to present up to four CF's in ears, using 500, 1000, 2000 and 4000 Hz with eight different MF's. The MF's vary for each ear and CF. When suprathreshold level (60 dB SPL) stimuli were used, there were no difference in response amplitude for the single-tone-alone condition, four stimuli combined in one ear, or four stimuli combined in two ears (Cone-Wesson, 2003:271; Sninger & Cone-Wesson, 2002:313). On average, an 18 dB difference between behavioral thresholds for the single tones and the ASSR thresholds was found when two CF's were presented simultaneously. The major advantage of this technique is that by simultaneously presenting multiple stimuli, (e.g. four stimuli in each ear for a total of eight), multiple responses can be recorded during the time normally required to record one (John et al., 2002:247; Dimitrijevic et al., 2000:207). Figure 2.4 illustrates the multi frequency ASSR.

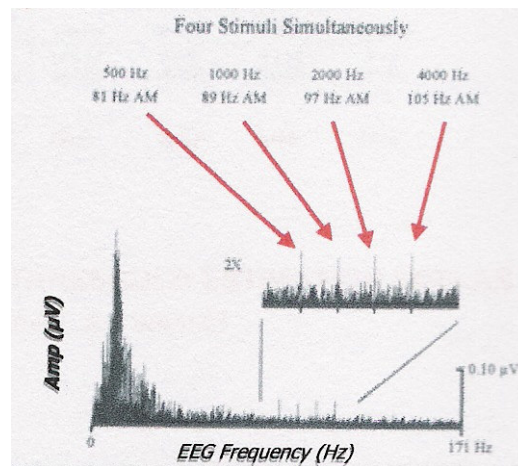


Figure 2.4 Multiple ASSR (From Stapells, 2004: conference presentation).

2.3.2.2 *Threshold determination*

The presence or absence of a response is determined automatically and objectively, using detection protocols that compare the response to the background EEG activity (Picton, 2002:65; Rance, 1995:501). Automatic response detection protocols rely on computer algorithms which are applied to the recorded EEG signal to analyze the magnitude and phase of EEG activity corresponding to the modulation frequency of the tone and to determine the presence or absence of an ASSR (Cone-Wesson & Sninger, 2002:317).

Samples of EEG activity are recorded and analyzed as the continuous modulated tone is presented. In each EEG sample, the magnitude and phase of the EEG activity corresponding to the tone modulation frequency is quantified (Cone-Wesson & Sninger, 2002:317). The peaks in the resulting spectrum, and the amplitude and phase of the spectral peak, can be measured for phase coherence (PC). The phase of the major peak can be plotted on polar coordinates. The sine and cosine of the angles formed by each phase vector are calculated. PC values vary from 0.0 to 1.0 (Cone-Wesson & Sninger, 2002:317). When the sample phases are in phase with one another, there is a high coherence, and the value will be closer to 1.0. When the sample phases are random, there is low coherence and values are closer to 0. Usually when a significant level of $p < 0,05$ is obtained, the nil hypothesis is rejected, the samples can be considered phase locked or coherent, and an evoked response is determined to be present. Figure 2.5 shows a polar plot of phase coherence.

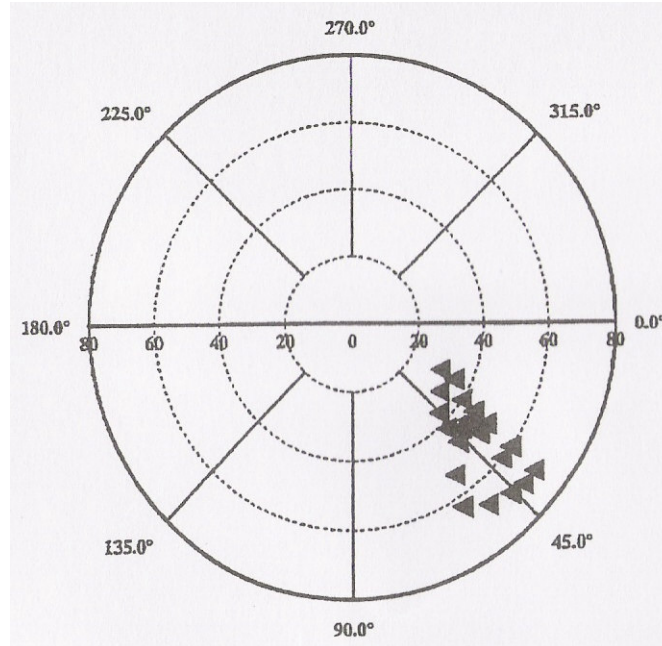


Figure 2.5 Polar Plot to Phase Coherence (from Sninger & Cone-Wesson, 2002)

By recording responses at descending intensities, a threshold or minimum response level can be obtained at the lowest intensity eliciting a response (Swanepoel et al, 2002:51).

2.3.2.3 *Current Clinical Application of the ASSR in Infants*

The major goal of evoked potential audiometry in infants is to predict or to estimate an infant's behavioral audiogram from evoked potential data – without any response from the patient or subjective interpretations of the results by a clinician (Dimitrijevic et al., 2002:206; Goldstein & Aldrich, 1999:109). Furthermore it is important to seek a procedure that may give the most information with regard to frequency range, signal magnitude range, response reliability, clear criteria for establishing threshold and validity in terms of the patient's actual auditory sensitivity. In the past two decades, ASSR techniques have become available as an option for objective hearing testing (Rance et al., 1998:499). Several researchers

found the ASSR to be a reliable method to obtain frequency specific estimates of behavioral pure tone thresholds in adults and older children (Dimitrijevic et al., 2002:205; Herdman & Stapells, 2001:41; Lins et al.; 1996:81 and Rance et al., 1995:499). Rickards et al. (1994:327) did research on the application of ASSR on well babies and other researchers did retrospective studies on the application of ASSR on infants (Vander Werff et al., 2002:227; Cone-Wesson et al., 2002:173) – comparing the ABR results with ASSR results. The clinical application of the ASSR will now be discussed – looking at three aspects, namely **detection, diagnosis and hearing aid fitting in infants.**

i. Detection

'It is almost axiomatic in the field of audiology that early detection and early intervention will yield a better functioning hearing impaired child' (Luterman, 1999:35). Over the past thirty years, several different procedures for screening newborns, including cardiac response, respiration audiometry, or alteration of sucking and startle responses have been used, investigated and found wanting (Luterman, 1999:37). Several methods of implementation of the high risk register approach have been used in the USA. It seems to identify about half of newborns with hearing loss (Northern & Hayes, 1997:21). Recently the ABR has been automated and the EOAE has been developed. Both these procedures can be rapidly administered, thus making universal screening for hearing impairment feasible (Luterman, 1999:39).

ASSR's may have an advantage over the ABR and EOAE's in newborn screening (Sninger & Cone-Wesson, 2002:318). EOAE's are thought to have an advantage over the click-evoked ABR, because it is more

“frequency-specific”. EOAEs appear to indicate cochlear integrity for at least the 1000 – 4000 Hz hearing range (Sninger & Cone-Wesson, 2002:318), however, EOAEs do not test neural function and cannot predict hearing threshold (Hall, 2000:26). The AABR on the other hand, only uses click stimuli, limiting estimation of hearing loss in different frequency ranges (Stapells, Gravel & Martin, 1995:361).

ASSR tests optimized for screening may overcome both the frequency limitations of click AABR and the site-of-lesion limitations of EOAE. Since ASSR tests use tonal stimuli, the evoked potential can be efficiently detected with well-documented algorithms, and accurate threshold estimates can be obtained (Sninger & Cone-Wesson, 2002:318; Rickards, 1994:327). The Rickards group recorded ASSR's from 337 normal full-term sleeping newborns to combined amplitude and frequency modulated tones. Responses were found most easily and consistently, recorded at carrier frequencies of 500 Hz, 1500 Hz and 4000 Hz with modulation frequencies between 60 Hz and 100 Hz. In this modulation frequency range, the response latencies were between 11 ms and 15 ms and the mean response threshold for the three carrier frequencies were found to be 41.36 dB HL, 24.41 dB HL and 34.51 dB HL respectively. These researchers suggested that the ASSR may be useful for frequency-specific automated screening in newborns when modulation rates exceeded 60 Hz. Cone-Wesson et al. (2002:276) used established tools (AABR and EOAEs) as the gold standard against which an ASSR screening protocol was compared. It was found that a three-frequency screening test (1000, 2000 and 4000 Hz) protocol could be completed within two minutes for each ear. Although the ASSR would seem to be an ideal screening tool, appropriate screening performance data (i.e., sensitivity and specificity)

in appropriate clinical samples will be needed before possible implementation (Stapells, 2005:56).

Audiogram estimation is clearly the most important clinical application of the ASSR at this time. The following section will focus on the diagnosis of hearing loss in infants

ii. Diagnosis

Various experiments have demonstrated that the ASSR can be reliably recorded at intensities near behavioral thresholds in sedated and sleeping adults (Dimitrijevic et al., 2002:205; Herdman & Stapells, 2001:41; Lins et al., 1996:81). Lins et al. (1996:81) used a test time of 3.2 to 12.8 minutes for each recording and found evoked response thresholds that were approximately 11 to 14 dB above behavioral thresholds in the frequency range of 500 – 4000 Hz. ASSR thresholds appear to approach behavioral thresholds more closely with hearing losses of approximately 60 dB HL or higher. Rance et al. (1995:500) recorded ASSR thresholds within 11 to 20 dB of the behavioral thresholds in a range 1 to 4 kHz and approximately 11 to 40 dB at 500 Hz in subjects with a hearing loss of 60 dB or more. In subjects with hearing losses below 60 dB HL, ASSR thresholds were found over a wider range.

Several investigators obtained ASSR thresholds from infants who were not at risk for hearing loss. There were some differences in age of the infants between the studies – Rickards et al. (1994:327) tested infants younger than 7 days. This group of investigators found ASSR thresholds from 32 dB SPL (1500 Hz) to 53 dB SPL (500 Hz). Lins et al. (1996:81) tested the age range of 1 to 10 months and found thresholds from 26 dB SPL (2000 Hz) to

58 dB SPL (500 Hz). Cone-Wesson et al. (2002:260) tested at a mean age of 11.5 months and had similar results: thresholds varied from 29 dB SPL (2000 Hz) to 45 dB SPL (500 Hz). The ASSR evoked responses offers definite advantages over techniques that require short duration stimuli (Rance et al., 1998:49). The ASSR is evoked by frequency-specific stimuli (Cone-Wesson, 2003:267 & Hood, 1998:117). This is because the steady state stimuli are continuous tones that do not suffer the spectral distortion problems associated with brief tone bursts and clicks (Rance et al., 1998:49). This specificity allows testing across the audiometric range and the generation of evoked potential audiograms, which in subjects with hearing loss, can reflect the configuration of the loss accurately (Rance et al., 1995:500).

Rance et al. (2005:297) and Rance et al. (1998:506) demonstrated the advantages of using the ASSR to determine residual hearing thresholds for those infants and children from whom a click ABR could not be evoked (at 100 dBnHL). In the 1998 study, completed by Rance et al., ASSR's were obtained using CF's of 250-4000 Hz with MF's of 90 Hz. The average discrepancy between ASSR and behavioral threshold ranged only 3 to 6 dB with larger discrepancies found at 250 and 500 Hz. ASSR thresholds were within 20 dB of pure tone thresholds for 99% of the comparisons and 10 dB or less for 82% of the comparisons. Rance et al. (2005:297) demonstrated results consistent with the previous study. Overall, the findings showed a strong correlation between ASSR threshold and behavioral hearing threshold levels. Pearson *r* correlation coefficient values ranged from 0.96 to 0.98 across the test frequencies in subjects with hearing loss. These findings demonstrated the efficacy of ASSR's for estimating the audiogram in infants and children who can benefit from amplification of their residual hearing (Singer & Cone-Wesson, 2002:316).

The determination of air-conduction (AC) and bone-conduction (BC) thresholds is a mainstay of clinical audiology (Cone-Wesson, Rickards, Poulis, Parker, Tan & Pollard, 2002:271). It is therefore important to determine the conductive component to an infant's hearing loss (Jeng, Brown, Johnson & Vander Werff, 2004:68), particular in infants and young children, who have a high incidence of middle ear disorders, causing conductive hearing loss (Cone-Wesson et al., 2002:271). The ASSR can be presented using both AC and BC transducers (Picton & John, 2004:542). Jeng et al. (2004:68) and Cone-Wesson et al. (2002:271) have shown a strong correlation between that of the ASSR bone conduction gap and audiometric estimates of air bone gap. Using the ASSR in this manner provides additional information about the nature of the hearing loss.

A further advantage of the ASSR, important for the application in infants, as cited by Rance (1995:506), is the speed in which a response can be detected. Responses could be detected within 20 – 90s after onset of the stimulus. Van der Reijden, Mens & Snik (2005:300) concluded in their summary of test time in the infant population that it approximately took between 3.2 to 12.8 minutes per ear, if four carrier frequencies were tested. This fast test time reduces the need to have the infant asleep or under sedation for long periods of time. As a result, the clinician is more likely to obtain all the information that is required before the subject awakens, and within one testing period (John et al., 2004:551; Rance et al., 1995:506).

A distinguishing and advantageous feature of the ASSR technique is that objective detection algorithms rather than visual detection methods are always used to determine presence or absence of a response (Sninger & Cone-Wesson, 2002:316; Lins et al., 1996:82). This is a particular advantage

for techniques claiming to be “objective” in nature as accurate information with regards to the configuration of the hearing loss is necessary to develop a habilitation program, such as the use of amplification.

iii. The ASSR in pediatric hearing aid fittings

Another application of the ASSR is when rehabilitation has started and hearing aids have been fitted according to the electrophysiologic targets. Picton (1998:315) and Glockner in Cone-Wesson (2003:272) showed that ASSR's could be recorded when stimuli were presented simultaneously through a sound-field speaker and amplified using a hearing aid. Picton et al. (1998:315) recorded responses at carrier frequencies of 500, 1000, 2000 and 4000 Hz in a group of 35 hearing-impaired children using hearing aids. The physiologic responses were recorded at intensities close to the behavioral thresholds for sounds in the aided condition, with average differences between the physiologic and behavioral thresholds of respectively 17, 13, 13, and 16 dB for carrier frequencies 500, 1000, 2000 and 4000 Hz. While there were discrepancies between behavioral (aided) threshold and ASSR (aided) threshold, it appeared to be no greater than those found when stimuli were transduced by earphones (Sninger & Cone-Wesson, 2002:319). Their findings suggest that it would be possible to measure functional gain of hearing aids on the basis of ASSR threshold predictions. The Picton group (1998) used a multiple-simultaneous stimulus technique and for some subjects, responses were only found at high suprathreshold levels or were absent. Retest with single AM tones in these cases, showed better correspondence between pure tone and ASSR threshold. This technique shows great promise as a way to assess aided

thresholds objectively in subjects who cannot reliably respond to behavioral testing.

Although hearing loss is commonly assessed using pure tone thresholds, the most debilitating aspect of a hearing loss is difficulty in speech perception (Dimitrijevic, John & Picton, 2004:68). A necessary first step in the perception of a word is to discriminate changes in the frequency and amplitude of a sound. The ability of the brain to detect changes in frequency and amplitude may be assessed by recording ASSR's to modulations in the frequency and amplitude of supra-threshold tones (Dimitrijevic, John & Picton, 2004:68). In this particular study independent amplitude and frequency (IAFM) modulation of tones stimulus parameters were adjusted to resemble the acoustic properties of everyday speech to determine how well responses to these speech-modulated stimuli were related to word recognition scores (WRS). The correlations between WRS and the number of IAFM responses recognized as significantly different from the background were between 0.70 and 0.81 for the 40 Hz stimuli, between 0.73 and 0.82 for the 80 Hz stimuli, and between 0.76 and 0.85 for the combined assessment of 40 Hz and 80 Hz responses. They concluded their research, stating that IAFM responses are significantly correlated with WRS and that it may provide an objective tool for examining the brain's ability to process the auditory information needed to perceive speech.

2.3.2.4 Critical evaluation of the ASSR

The ASSR shows promise in addressing some of the limitations of the ABR; however it still needs to be validated in the clinical field – especially in the pediatric field, before it can be recommended for clinical use.

The limited database for infants with hearing loss is a matter of great concern. According to Stapells (2004: conference presentation), relatively few studies are available. Of these studies the total sample size is not large – especially for the multiple ASSR. Of these studies comparisons were made with the click ABR, which is inappropriate as this measure do not give frequency specific information. Only two studies compared infant ASSR to tone evoked ABR, but only for 500 Hz. Only a few studies included a comparison between the ASSR and behavioral threshold. All of above studies included only Air Conduction (AC) ASSR. No information is available on Bone Conduction (BC) in infants with hearing loss or infants with conductive and/or mixed hearing losses (Stapells, 2004: conference presentation). Limited information is available about infants with mild or moderate hearing loss.

Some recent studies showed the possibility of spurious/artificial ASSR's at high intensity stimuli (Small & Stapells, 2004:611; Gorga et al., 2004:302; Jeng et al, 2004:67; Picton & John, 2004:541). ASSR thresholds were measured in subjects who had no behavioral responses to sound at the limits of pure-tone audiometers. It may thus appear that some responses in infants with profound SNHL may not be auditory. Some of these spurious responses may be due to aliasing, thus a signal processing issue and other spurious responses are likely physiologic and may be a vestibular response (Stapells, 2004: conference presentation). Clinically this may be of little consequence, as these patients will in all likelihood receive cochlear implants (Gorga et al., 2004:302). The manufacturer was made aware of this problem and correction was made to the software (Personal correspondence: Biologic systems).

Although Jeng et al. (2004:67) and Cone-Wesson et al. (2002:271), recorded ASSR using BC, with their results demonstrating a good correlation between estimated air-bone gap (ABG) using pure tone audiometry and ASSR, the subjects used in these studies were adults and therefore no information on BC ASSR are available for infants. Data from subjects with profound hearing loss also demonstrated that the levels where stimulus artifacts become problematic, were relatively low (Jeng et al., 2004:67; Small & Stapells, 2004:611). Small & Stapells (2004:622) concluded their study that although ASSR's appear to be promising, bone-conduction ASSR's will not be ready for clinical use until there are normative threshold data for infants of different ages.

Optimal stimuli and analysis is not yet determined. According to Stapells (2004: conference presentation), this, in itself, is not a problem. However, the small clinical database available has used different protocols, e.g. single vs. multiple ASSR's, F-test analysis, noise criteria, stopping rules, to name a few. Another concern is the duration of the stimulus when assessing the profound SNHL as the duration of high-intensity stimulation could result in acoustic trauma (Stapells, 2004: conference presentation).

Research studies (Rance et al., 2005:297; Cone-Wesson, 2002:185; Dimitrijevic et al., 2002:205; Vander Werff, 2002:227) show that the ASSR perform in the clinical pediatric setting and the results to the data from these research studies are very promising. The concerns mentioned above are surmountable and used in conjunction with the ABR, the ASSR can provide additional information about the configuration and degree of any existing hearing loss. Some questions still remain:

The neural generators of the response are still in dispute, particularly as a function of MF. Cone-Wesson (2002:281) feels that this should not limit adoption of the ASSR in the clinic as the precise sites and structures involved in the ABR have not been fully defined either. The effect of neuro-development and neuro-maturation insult on the ASSR is a critical issue for investigation. A related issue is the definition of normal “threshold” for the ASSR as a function of age – as this is expected to vary with both maturation of the auditory system periphery and the central auditory nervous system.

ASSR's have not yet been exploited for neuro-otologic diagnosis. It is likely that measures of phase coherence and also of latency could be used to indicate retrocochlear abnormalities for suprathreshold stimuli (Sninger & Cone-Wesson, 2002:319).

Lins & Picton (1995:420) investigated the physiology underlying the ASSR – using modulation rates between 150-190 Hz. Equal contributions between the brainstem and cortical areas were noted at these higher modulation rates. These researchers hypothesize that some insight may be gained into pathology of the auditory system up to cortical level.

Research is still required to establish whether single modulated tones offer higher frequency specificity at high stimulation intensities. Gorga, Neely, Hoover, Dierking, Beauchaine and Manning (2004:306) cautions the interpretation of high-level ASSR threshold measurements – using the multi-frequency system, as it may not provide information about peripheral hearing. Clinically this may be of little consequence, as these patients with “responses” observed at such high levels will in all likelihood receive cochlear implants. Research is also required to establish whether aided

thresholds can be obtained from cochlear implant users, using an adapter cable, to maximize usage of electrode configurations in the maps (Marais, 2003:37).

2.3.2.5 *Summary of the ASSR application in pediatric audiology*

As a conclusion to this critical evaluation of the ASSR, Table 2.3 indicates the advantages as well as the limitations of the ASSR.

Table 2.3 Advantages and limitations of the ASSR

| Advantages | Limitations |
|---|--|
| Diagnosis | |
| <ul style="list-style-type: none"> • Frequency specific – approximate pure tones • Stable – resistant to state of consciousness • Objective automatic detection of response • Distinguish between severe and profound losses • Relatively fast procedure | <ul style="list-style-type: none"> • Requires clinical validation – especially in the pediatric field: <ul style="list-style-type: none"> ➢ Bone-conduction ➢ Duration of high-intensity stimuli ➢ New equipment ➢ Spurious/artificial ASSR • Cannot differentiate between hearing loss of peripheral origin and those with neural transmission or retrocochlear origin |
| Validation Process | |
| <ul style="list-style-type: none"> • Provides ability to evaluate hearing aids | <ul style="list-style-type: none"> • Requires clinical validation <ul style="list-style-type: none"> ➢ Very limited research reports on applicability of this unconventional application of the ASSR |

It is evident that the ASSR shows great promise for the clinical field of pediatric audiology as various researchers have demonstrated the advantages of the ASSR, over other AEP techniques, such as the ABR to use as an objective procedure to identify the nature, degree, symmetry and configuration of the hearing loss in infants as well as validation of hearing aids. It is imperative however that more research validate this procedure against the ABR – the current gold standard in clinical practice for pediatric audiology.

2.4 CONCLUSION

The need for a technique to estimate frequency-specific hearing thresholds in a clinically time-efficient manner in the difficult-to-test populations has long been a priority in the field of pediatric audiology (Hayes & Northern, 1997:234). Auditory Evoked Potentials have been used in diagnostic audiology for the past three decades and it is clear that in the field of objective audiology, large strides have been made in addressing this important need.

The most widely used AEP technique currently used to determine hearing thresholds in infants is the ABR. This technique – using a click stimulus, can provide a general evaluation of hearing sensitivity in the high frequency region (2 – 4 kHz). By using tone burst stimuli, more frequency specific information will be provided. Although the ABR is a valuable tool, it presents with important limitations.

The ASSR have been used in audiology research centers around the world for two decades and has demonstrated promise in addressing some of the limitations of the ABR (Cone-Wesson et al., 2002:273). The results from

clinical studies have shown that ASSR thresholds can be used to predict pure-tone threshold in sleeping infants and young children (John et al., 2004; Rance et al., 2002; Rance et al., 1998; Rance et al., 1995). ASSR should therefore have an increasing role in the follow-up and diagnostic evaluation of infants who have failed newborn hearing screening. Used in conjunction with ABR (AC and BC tone-evoked ABR), ASSR's provide additional information about the contour and degree of any existing hearing loss (Stapells, 2004: conference presentation; Cone-Wesson et al., 2002:281). The ASSR also shows great promise as a way to validate hearing aid fittings objectively in subjects who cannot reliably respond to behavioral testing, but research data is still limited.

2.5 SUMMARY

This chapter aimed to orientate the reader on the topics of relevance and to provide a critical evaluation and interpretation of the relevant literature. In order to achieve this, the most widely used AER technique for estimating auditory thresholds in infants, namely the ABR was described, evaluated and discussed. Subsequently the importance of the hearing aid fitting process was discussed – describing the different, but equally important aspects of verification and validation. The role of each aspect in the hearing aid fitting process was clarified. Lastly the ASSR was discussed as an AEP promising to address the current limitations of the ABR. Finally the general ideas of the chapter were summarized in the conclusion.