

# Aided Cortical Auditory Evoked Potentials for Hearing Instrument Evaluation in Infants

*Suzanne C. Purdy, Richard Katsch, Harvey Dillon, Lydia Storey,  
Mridula Sharma and Katrina Agung*

## Why We Need Objective Methods for Hearing Instrument Evaluation in Infants

With the widespread implementation of universal newborn hearing screening programs there is a need for reliable, objective techniques for fitting and evaluating hearing instruments in young infants. After hearing loss is diagnosed, fitting of hearing instruments can occur when infants are as young as five weeks old (Yoshinaga-Itano 2004). At this stage of development it is difficult to assess hearing using behavioral techniques and it is not yet known which hearing instrument fitting approach is optimal in such young infants (Snik and Stollman 1998). Because of the lack of reliable behavioral information audiologists may be tempted to fit hearing instruments “conservatively” in young infants, with less gain and output than would normally be prescribed for children and adults who are able to give reliable behavioral responses while wearing hearing instruments.

Objective measures such as auditory evoked potentials offer the possibility of evaluating the effectiveness of hearing instruments in infants and other children who have a limited behavioral repertoire due to developmental delay or other disabilities. This chapter describes the range of auditory evoked potentials, previous research that attempted to use evoked potentials to evaluate hearing instruments, and recent work showing that cortical auditory

evoked potentials can be used to evaluate hearing instruments in young infants.

## Auditory Evoked Potentials and Hearing Instrument Evaluation

Auditory evoked potentials (AEPs) represent summed neural activity in the auditory pathways in response to sound. Because they provide an objective measure of the brain’s response to sound, AEPs are an ideal tool for investigating auditory function in young infants. AEPs can be classified as “obligatory” or “discriminative”. Obligatory AEPs are evoked by *repeated* sounds such as clicks, brief tones, or speech stimuli. Obligatory AEPs are usually classified in terms of their latencies, or the time of occurrence after presentation of a stimulus (Hall 1992). The auditory brainstem response (ABR) is an early evoked potential originating in the auditory nerve and the brainstem auditory pathways that occurs within about 10 ms after stimulus onset.

There was considerable interest in using ABR to determine hearing instrument effectiveness during the 1980s and early 1990s (Beauchaine, Gorga, Reiland and Larson 1986; Bergman, Beauchaine and Gorga 1992; Davidson, Wall and Goodman 1990; Hecox 1983; Kiessling 1982; Gerling 1991; Gorga, Beauchaine and Reiland 1987; Kileny 1982; Mahoney 1985). Unfortunately, these studies highlighted some problems with the use of ABR for assessing amplification. The brief stimuli (clicks and brief tonebursts) that are optimal for ABR recordings may not activate the hearing instrument’s compression circuitry in the

---

*Address correspondence to:* Suzanne C. Purdy, Ph.D., Speech Science, (Department of Psychology), Tamaki Campus, The University of Auckland, Private Bag 92019, Auckland, New Zealand. [sc.purdy@auckland.ac.nz](mailto:sc.purdy@auckland.ac.nz)

same way as longer-duration speech sounds (Brown, Klein and Snyder 1999), and may be treated as “noise” by hearing instruments with speech detection algorithms (e.g., Alcantara, Moore, Kuhnelt and Launer 2003). Compared to speech, clicks have a much higher peak level compared to their rms (root mean square) level. Consequently hearing instruments will amplify clicks differently than they would speech stimuli. Due to its short latency, the ABR can also be contaminated by stimulus artifact due to electromagnetic pickup of the loudspeaker- and hearing-instrument-transduced signal by the ABR recording electrodes. For these reasons attempts to use the ABR to evaluate hearing instruments have largely been abandoned.

The middle latency response (MLR) occurs within about 100 ms after stimulus onset and primarily represents responses from the thalamocortical pathways and primary auditory cortex (Kraus and McGee 1993). The MLR can be used to assess hearing sensitivity, but is more affected by subject state (McGee and Kraus 1996) and is more variable, both within and between subjects than ABR (Dalebout and Robey 1997; Kavanagh, Domico, Crews and McCormick 1988). Thus, the MLR is also not an ideal tool for objective hearing instrument evaluation.

Like the ABR, the fast rate auditory steady state evoked response (ASSR) recorded in sleeping infants primarily reflects activity in the auditory brainstem (Herdman *et al.* 2002). ASSRs generated by amplitude-modulated sinusoids have been used to measure unaided versus aided hearing thresholds in hearing impaired children (Picton *et al.* 1998). Recently, Dimitrijevic, John and Picton (2004) found that the number and amplitudes of ASSR components evoked by independent amplitude and frequency modulation (IAFM) of tones were related to word recognition scores in adults. The IAFM parameters were selected so that the stimulus had acoustic properties similar to everyday speech. Dimitrijevic *et al.* concluded that the ASSR evoked by the IAFM stimulus may provide an objective tool for examining the brain’s ability to process the auditory information needed to perceive speech. Depending on the progress of this research, this approach may be useful for infant hearing instrument evaluation at some stage in the future.

“Discriminative” AEP such as mismatch negativity or P3 are evoked by a *change* from a frequent “standard” stimulus to an infrequent “deviant” stimulus. Oates, Kurtzberg and Stapells (2002)

investigated mismatch negativity (MMN) and P3 discriminative evoked potentials in response to /ba/ and /da/ speech stimuli in adults with mild to severe/profound hearing loss who wore hearing instruments. Sensorineural hearing loss caused amplitude and latency response changes for the earlier (N1, MMN) cortical responses. The impact of sensorineural hearing loss was greater, however, for the later evoked potentials (N2/P3) that reflect higher-level stimulus processing. Oates *et al.* (2002) reported some preliminary data showing the largest aided improvements in cortical response detectability, amplitudes, and latencies for adults with greater degrees of hearing loss, and concluded that cortical evoked potentials may provide a useful objective diagnostic index for measuring amplification benefits.

The discriminative evoked potentials such as MMN are extremely useful research tools that are advancing our understanding of the central auditory processes underlying auditory discrimination (Kraus and Cheour 2000). Based on our current knowledge, however, MMN does not appear to be an ideal tool for clinical evaluation of auditory function in individual children. Even in children with normal hearing sensitivity and normal auditory processing MMN is not always present (e.g., Kraus, Koch, McGee, Nicol and Cunningham 1999; Picton, Alain, Otten, Ritter and Achim 2000; Sharma, Purdy, Newall, Wheadall, and Beaman 2004). With improvements in our understanding of how to optimize stimulus and recording parameters this situation may change in the future, however (see, for example, Näätänen, Pakarinen, Rinne and Takegata 2004).

## Obligatory Cortical Auditory Evoked Potentials (CAEP)

In adults the obligatory CAEP waveform consists of three main peaks (P1-N1-P2) that occur within about 300 ms after stimulus onset. CAEP thresholds are routinely used by clinicians to estimate hearing sensitivity in adults because P1-N1-P2 response thresholds agree very well with audiometric thresholds determined behaviorally (Cody, Klass and Bickford 1967; Davis 1965; Tsu, Wong and Wong 2002). Currently the most common clinical application of CAEP testing is for objective threshold estimation in adults thought to have a non-organic or exaggerated hearing loss (Rickards and De Vidi 1995).

CAEPs are not generally used for objective

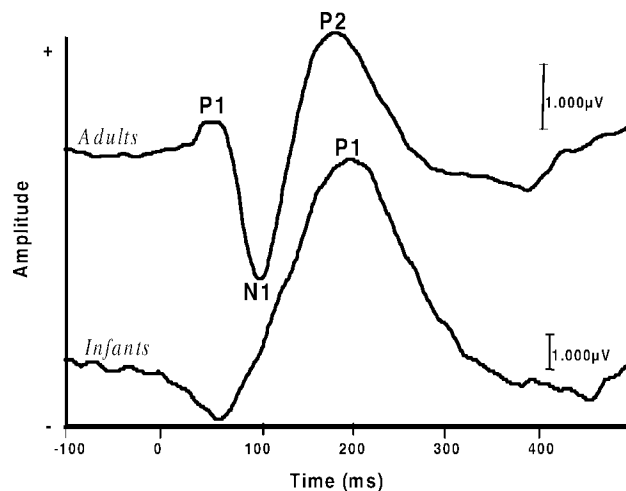
---

audiometry in infants, although they presumably could be. The two evoked potential techniques currently widely used for objective audiometry in infants are ABR and, to a lesser extent, ASSR (Cone-Wesson 2003). Because infants are usually tested when they are asleep, ABR and ASSR are more suitable tools for assessing hearing sensitivity in very young infants who sleep often. The use of CAEP for threshold estimation in infants and difficult-to-test children who do not sleep well for ABR or ASSR testing, or who cannot be sedated, is a possibility that has not been explored in the recent literature.

Cortical evoked potentials are affected by both arousal level and attention and are typically recorded when the person being tested is awake and alert or in a light sleep stage (Cody *et al.* 1967). Kushnerenko *et al.* (2002) noted that the same CAEP recordings are obtained in “active sleep” versus wakefulness in newborn infants. Kushnerenko *et al.* defined active sleep as being characterized by “closed eyes, irregular respiration, rapid eye, and occasional body movements, and mixed or low-voltage irregular continuous EEG patterns” (Kushnerenko *et al.* 2002, p.48). Unfortunately, audiologists would not normally have equipment or expertise for monitoring the electroencephalogram (EEG) to determine sleep stage. Since it is difficult to determine sleep stage, a good solution is to perform cortical evoked potential testing when the infant, child, or adult being tested is awake.

## Developmental Changes in CAEP

The developmental time course of the CAEP in infants has been investigated reasonably extensively (e.g., Kurtzberg, Hilpert, Kreuzer and Vaughan 1984; Novak, Kurtzberg, Kreuzer and Vaughan 1989; Ponton, Don, Eggermont, Waring and Masuda 1996; Sharma, Kraus, McGee and Nicol 1997). Because the cortical potentials are generated by multiple brain regions including primary auditory cortex, auditory association areas, frontal cortex and subcortical regions (Stapells 2002) that mature at different rates, there are complex changes in the morphology, scalp distribution and amplitude and latency of the P1-N1-P2 waves with maturation (Cunningham, Nicol, Zecker and Kraus 2000; Ponton, Eggermont, Kwong and Don 2000). At birth and up to about 7 years of age, wave P2 is absent and the response is dominated by a large, late P1 response (e.g., Ponton *et al.* 1996).



**Figure 1.** Grand average adult ( $n=12$ ) and infant ( $n=20$ , 3–7 months) CAEP waveforms recorded at Cz, evoked using a 500 Hz tonal stimulus presented at 65 dB SPL. Stimulus rise, fall, and plateau times were each 20 ms and inter-stimulus interval was 750 ms.

These differences between the adult and infant waveforms are illustrated in figure 1.

Kurtzberg *et al.* (1984) reported that CAEPs were present in all well babies in their study and in 34 of 35 very low birthweight babies at age 2 months. Pasman, Rotteveel, de Graaf, Maassen and Notermans (1991) measured cortical potentials in preterm babies at 35–37 weeks conceptional age and also reported good detectability rates (95%) for CAEPs in infants. There are maturational changes in the latency of the large P1 peak that dominates the CAEP in young children across the school age range and into adolescence (Sharma *et al.* 1997; Ponton *et al.* 2000), but the greatest reductions in P1 latency occur in the preschool period (Sharma, Dorman and Spahr 2002). In infants P1 occurs at approximately 200–250 ms and is followed by a late negativity at about 350–450 ms (e.g., Kurtzberg *et al.* 1984; Kushnerenko *et al.* 2002; Pasman *et al.* 1991).

## Validation of Hearing Instruments in Young Infants

Hearing instrument prescriptive procedures aim to make the full frequency range of speech detectable and comfortably loud to the hearing-impaired child (e.g., Ching and Dillon 2003; Seewald and Scollie 2003). Pediatric audiologists have access to verification tools such as calculations of real ear gain and

output based on the real ear to coupler difference (RECD) measurements (Tharpe, Sladen, Huta and McKinley Rothpletz 2001) that can be used in combination with an appropriate prescriptive target to ensure that access to the speech spectrum is optimized. Once hearing instrument prescriptive targets are met, ideally the audiologist would have some method for ensuring that speech is detectable and that speech sounds can be discriminated by individual children. Any methods relying on calculation, however, rely on having accurate estimates of hearing threshold, which are not always available, particularly for infants with severe/profound hearing loss. Even when thresholds are accurately known, where the level of amplified speech is above but close to threshold, the sensation level needed for speech sounds to be reliably detected and discriminated from other speech sounds is not known.

Prescriptive targets are designed for average ears and it is commonplace for “fine tuning” to occur when adults are being fitted with hearing instruments since there are individual differences in preferred gain and in perceptions of aided speech intelligibility and sound quality (Byrne 1986; Leijon, Lindkvist, Ringdahl and Israelsson 1990). For adults, clinicians would normally follow up the real ear verification procedure with some behavioral checks to ensure that the hearing instruments are optimally adjusted for the individual listener. Unfortunately this is difficult to do in young infants, and clinicians have relied on parental reports and questionnaires to ensure that the hearing instruments improve listening and do not cause loudness discomfort (e.g., Harrison 2000). Houston, Pisoni, Kirk, Ying and Miyamoto (2003) have developed a visual habituation procedure for investigating speech detection and discrimination in 6 and 9 month old normal hearing infants and deaf infants before and after cochlear implantation. This visual habituation approach has great promise as a tool for behavioral assessment of speech perception in infants. It is not yet clear, however, whether reliable individual data can be obtained in infants younger than 6 months using this approach, even for a single speech contrast, let alone for a range of sounds.

The work of Yoshinaga-Itano and her colleagues (e.g., Yoshinaga-Itano, Sedey, Coulter and Mehl 1998; Yoshinaga-Itano 2003) who have looked at speech and language outcomes of early- versus late-identified hearing impaired children suggests that the first six months of listening may be especially important for speech and language development. This timeframe is

consistent with the research evidence from cross-linguistic studies of the speech perception abilities of young infants. By 8–10 months of age infants with normal hearing are already “tuned in” to the speech contrasts of their native language and have reduced ability to discriminate non-native speech contrasts compared to younger infants (e.g., Werker and Tees 2002). Thus, by the time infants are old enough to give reliable, comprehensive behavioral responses in the clinic to indicate what they can and can’t hear, an important period for normal linguistic development has already passed.

Objective tools such as auditory evoked potentials can be used to ensure that infants do have access to the speech signal in the early months. The purpose of the current research investigating the use of aided cortical assessment to evaluate hearing instruments in infants is not to *verify* hearing instrument fitting. This could be done by measuring aided and unaided CAEP thresholds and taking the difference between these as an indication of functional gain, although the gain estimated will be the gain that applies at threshold rather than at typical speech levels, if those are different. This would be similar to the approach used by Picton *et al.* (1998) who measured aided thresholds using ASSR evoked potentials. If clinicians use individual RECD measures for their calculations of gain and maximum output targets they should be able to accurately predict aided hearing, assuming the initial estimates of hearing sensitivity are correct (Scollie, Seewald, Cornelisse and Jenstad 1998; Seewald, Moodie, Sinclair and Scollie 1999). Hence, a more useful application of aided evoked potential testing is to *validate* the hearing instrument fitting, rather than objectively measure aided hearing thresholds.

## **Why use CAEP to Evaluate Hearing Instruments in Infants?**

The relationship between pure tone audiometric thresholds and CAEP thresholds is well established. The relationship between CAEPs and speech perception is less well understood, but a number of different lines of evidence indicate that CAEPs relate well to behavioral measures of auditory perception. These studies have examined stimulus and auditory training effects on CAEPs, as well as the relationship between CAEP characteristics and perception. The CAEP waveform is affected by changes in speech stimulus parameters such as voice onset time and

---

place of articulation (e.g., Tremblay, Friesen, Martin and Wright 2003). Changes in speech-evoked obligatory CAEP occur with listening training that produces improved behavioral speech discrimination (e.g., Tremblay and Kraus 2002). Cortical evoked potentials correlate well with auditory perception in cases of “central deafness” (Bahls, Chatrian, Mesher, Sumi and Ruff 1988; Hood, Berlin and Allen 1994). A clear relationship between speech perception and the presence of CAEP has also been demonstrated in children with auditory neuropathy/dys-synchrony (Rance, Cone-Wesson, Wunderlich and Dowell 2002). The children in the Rance *et al.* study either showed no open-set speech perception ability (7/15 cases), or speech performance levels similar to a control group of children with sensorineural hearing loss (8/15 cases). About half of children with auditory neuropathy/dys-synchrony had normal CAEPs. In all cases with cortical responses present at normal latencies, speech perception ability was reasonable, and was similar to that seen in age-matched children with sensorineural hearing loss. The other children with auditory neuropathy/dys-synchrony who had absent CAEP had negligible speech perception.

The purpose of using aided CAEP to validate the hearing instrument fitting is to show that speech stimuli across the speech spectrum evoke a neural response at the level of the auditory cortex and therefore are likely to be perceived. If the neural responses evoked by different speech stimuli differ, as evidenced by differences in the CAEP waveforms, this suggests that the stimuli should also be discriminated from each other. At a very simple level, the presence of speech-evoked CAEPs indicates that speech stimuli have been detected (Hyde 1997). Differences in the aided cortical responses to different speech stimuli indicate that the underlying neural representation of the stimuli differs. If the neural representations of the stimuli differ at the level of the auditory cortex the infant should be able to behaviorally discriminate the stimuli, if other abilities are intact. Hence, it is possible that CAEP can be used for objective validation of hearing instrument fitting in young infants to ensure that speech sounds are both detected and discriminated. The assumption underlying this approach is that a hearing aid fitting that causes CAEPs for different speech sounds to be present and differentiated is likely to be more useful to the child than a fitting where the responses are either absent or undifferentiated. This is supported, but by no means proven, by our observations that certain

speech sounds produce differentiated responses for children with normal hearing. A further issue, which we are yet to investigate, is whether it is reasonable to expect an optimally fitted hearing aid to produce a response with normal morphology (shape, amplitude, latency). As previous deprivation to sound is known to cause abnormal latencies (Sharma *et al.* 2002), it is certainly unreasonable to *require* morphology to be normal before being satisfied that the fitting is optimal.

Obligatory cortical evoked potentials seem to be an ideal objective tool for aided hearing instrument evaluation because they are reliably present in young infants, they correlate well with perception, they can be evoked by a range of speech stimuli, and they seem to be sensitive to differences between speech stimuli. Aided cortical testing is not a new idea. Many years ago, Rapin and Graziani (1967) suggested that clinicians use CAEP to evaluate the effectiveness of hearing instruments in deaf children. Gravel, Kurtzberg, Stapells, Vaughan and Wallace (1989) reported several case studies of hearing – impaired infants who had absent unaided CAEP to /ta/ and /da/ speech stimuli, and present aided CAEP. Gravel *et al.* noted that, although aided CAEP were present, in some cases they were reduced in amplitude compared to CAEPs recorded from children of the same age with normal hearing. Other responses had “atypical morphology”. Thus, aided cortical testing was able to provide useful information on the audibility of the amplified speech stimuli in these cases.

### CAEP in Infants with Normal Hearing and Aided CAEP in Infants with Hearing Loss

Over the past few years extensive investigations have been undertaken at the National Acoustic Laboratories in Sydney, Australia, to determine normative characteristics of tonal and speech-evoked CAEP in infants with and without hearing loss with a view to using aided CAEP testing clinically for hearing instrument evaluation in young infants (Purdy, Katsch, Storey, Dillon and Ching 2001; Purdy *et al.* 2003). Speech-evoked CAEP are recorded with the infant awake and seated on the caregiver’s lap. The caregiver is seated in a comfortable chair with loudspeakers delivering the stimuli at 45-degrees facing right and left ears. The person distracting the child sits in front between the two loudspeakers, on the

**Table 1.** Suggested stimulus and recording parameters for aided CAEP testing in infants.

---

Stimuli	30–100 ms speech sounds <i>or</i> 20 ms rise/fall, 20 ms plateau tones [if speech unavailable]
Stimulus level	65 dB SPL (rms) or higher [ensure that levels do not cause hearing instrument saturation]
Inter-stimulus interval	1125 ms
Transducer	Loudspeaker at 45 degrees azimuth [An equaliser is needed to ensure that the sound field is spectrally “flat” in the vicinity of the child]
EEG channels	vertex (Cz) – mastoid left hemisphere (C3) – mastoid [optional] right hemisphere (C4) – mastoid [optional]
EEG filter	High pass 0.1 Hz Low pass 30 Hz [ <i>or</i> 100 Hz online, 30 Hz offline digital filter]
Recording time window	100-ms pre-stimulus baseline 600-ms post-stimulus
Artifact rejection	Trials exceeding $\pm 100$ to 150 mV
Number of trials	50–100
Number of repeats	At least two

---

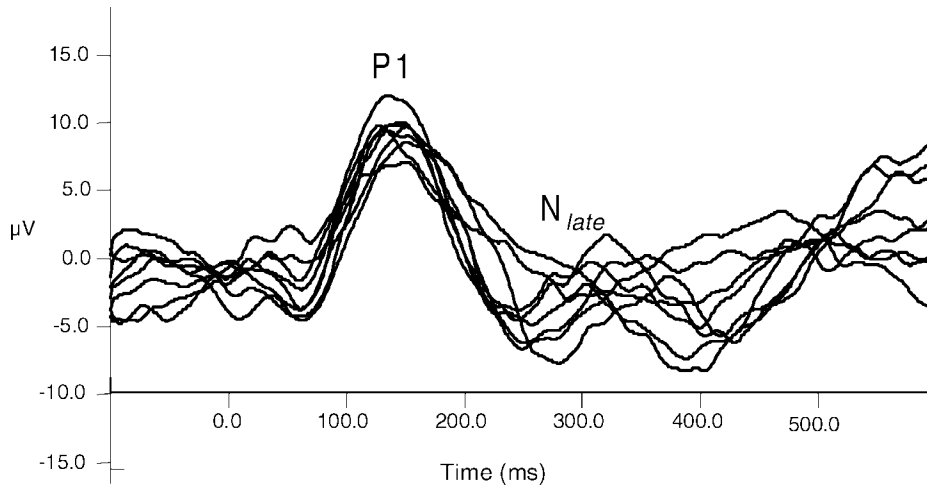
floor or on a low chair. Stimulus level is monitored using a sound-field microphone suspended from the ceiling above the chair, connected to a measuring amplifier in the observation room. Stimuli are typically presented at a conversational speech level of 65 dB SPL but can be presented at levels up to 85 dB SPL. To ensure that the spectral characteristics of the speech stimuli are not affected by room and loud-speaker characteristics, a graphic equalizer is used to adjust the levels across frequency bands to compensate for any variations from a flat frequency response. Electrodes are placed at up to three locations (vertex/Cz, left hemisphere/C3, right hemisphere/C4), referenced to the right ear and with a ground electrode on the forehead. Suggested stimulus and recording parameters are summarized in table 1. Robust CAEP can be recorded to a range of speech stimuli in individual 2–7 month old infants using these parameters..

Figure 2 shows an example of individual waveforms CAEP evoked by a range of 100-ms duration natural speech tokens ([i] as in *heed*, [a] as in *hard*, [u] as in *who’d*, [ɔ] as in *hoard*, [ʊ] as in *hood*, [m], [s], and [ʃ]) in a three-month old infant with normal hearing. Figure 2 shows that robust CAEP waveforms can

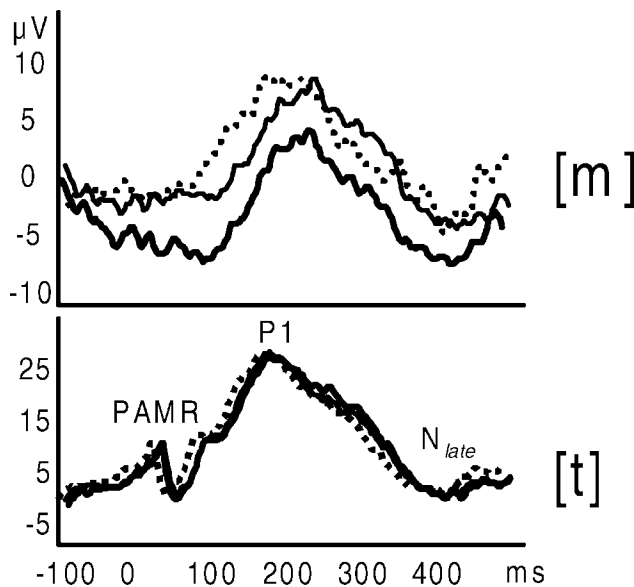
be obtained in individual infants to a range of speech stimuli. Each waveform in this example represents the average of two replications of 50 artifact-free responses to each stimulus (artifact rejection set at  $\pm 150$  mV in this example).

CAEP evoked by [m] and [t] speech stimuli recorded from another infant with normal hearing are shown in figure 3. The lower panel in figure 3 shows a clear post-auricular muscle response (PAMR) evoked by the [t] stimulus, early in the waveform, prior to the CAEP peaks. PAMR is optimally recorded from electrodes placed over the post auricular muscle located behind the pinna (O’Beirne and Patuzzi 1999). The PAMR in humans is likely to be a vestigial version of the Preyer reflex that causes the ears of some animals to move in response to sound (Gibson 1978). PAMR is often present in our evoked potential recordings from infants with normal hearing, when speech stimuli with a high frequency emphasis were used, such as [t], [g], [s], and [ʃ]. This is consistent with previous evidence for PAMR amplitude enhancement with high frequency stimuli (Patuzzi and Thomson 2000; Agung, Purdy, Patuzzi, O’Beirne and Newall in press). The cortical response to both [m] and [t] stimuli is dominated by the large positive

---



**Figure 2.** Individual CAEP evoked waveforms by a range of 100-ms duration natural speech tokens ([i] as in *heed*, [a] as in *hard*, [u] as in *who'd*, [ɔ] as in *hoard* and [ʊ] as in *hood*, [m], [s], and [ʃ]) in a three-month old infant with normal hearing recorded at Cz. Inter-stimulus interval was 1125 ms. Each waveform represents the average of 100 stimulus presentations (two replications of 50 averages,  $\pm 150$   $\mu\text{V}$  artifact rejection). There are differences in latencies and waveform morphology (e.g., the position of the late negativity “N<sub>late</sub>”) between stimuli.

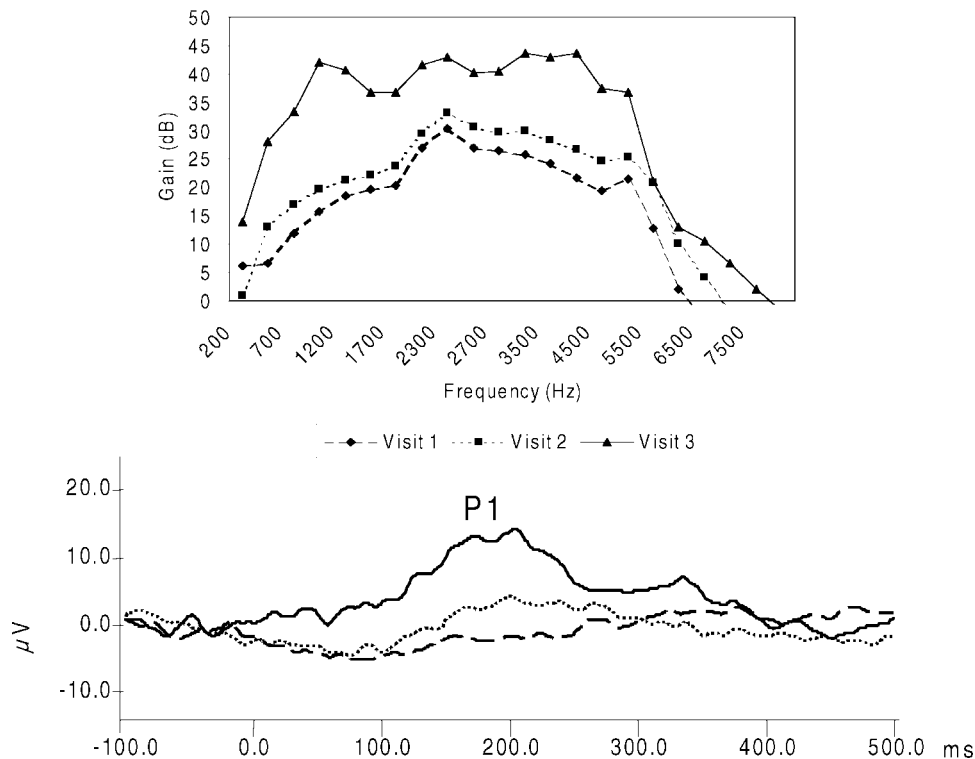


**Figure 3.** Representative individual CAEP evoked waveforms for [m] and [t] speech stimuli in a five-month old infant with normal hearing. Inter-stimulus interval was 750 ms. Each waveform represents the average of 200 stimulus presentations (two replications of 100 averages,  $\pm 100$   $\mu\text{V}$  artifact rejection). The solid line indicates the Cz (vertex) recording, dashed line = C3 (left hemisphere), and thin line = C4 (right hemisphere). The waveforms from the three electrode sites are very similar for [t] but differ slightly for [m] in this example. For this infant there are clear differences in peak amplitudes and latencies and waveform morphology (e.g., the position of the late negativity “N<sub>late</sub>”) between the [t] and [m] stimuli (note the difference in the amplitude scale). The [t] waveform contains a post-auricular muscle response (PAMR) in addition to the CAEP waveform.

P1 peak at about 200 ms. Figure 3 shows substantial differences in the waveforms evoked by [m] and [t]. This was consistently the case for the infants with normal hearing. These stimuli differ greatly in their spectral content (low versus high frequency content) and their temporal characteristics and hence it is not surprising that they produced very different cortical responses.

Aided cortical testing has been conducted for a

large group of infants and children whose hearing instruments have been fitted using the NAL-NL1 prescriptive procedure (Byrne, Dillon, Ching, Katsch and Keidser 2001). CAEPs are consistently present in infants and children with moderate sensorineural hearing loss. About half of those tested with profound hearing loss have aided CAEPs to 65 dB SPL speech stimuli. The waveforms in figure 4 show the improvement in CAEP morphology and amplitudes



**Figure 4.** Top panel shows gain settings for one of Case H's hearing instruments for three occasions over a two-month period when his CAEP waveforms were recorded. He was five months old when he was tested initially and was thought to have a bilateral moderate-severe sensorineural hearing loss. The bottom panel shows aided CAEPs recorded at the vertex (Cz) for the ear that was tested with this hearing instrument (with the other ear occluded). The stimulus for all three recordings was the speech stimulus [g] (32-ms duration, 750-ms inter-stimulus interval). The initial waveform recorded at Visit 1 shows no response. At Visit 2 there is a small cortical response associated with a small increase in hearing instrument gain. At Visit 3 the gain of the hearing instrument has been increased overall by approximately 15 dB and a clear CAEP is present. This gain increase occurred after the infant became old enough for behavioral testing using Visual Reinforcement Audiometry (VRA). The VRA hearing thresholds were consistent with the original ABR thresholds, but prior to VRA testing the hearing instrument had been adjusted "conservatively". The final gain settings are based on the NAL-NL1 prescription. Each waveform represents the average of 200 artifact-free trials (2 blocks of 100 stimuli,  $\pm 100$   $\mu\text{V}$  artifact rejection).

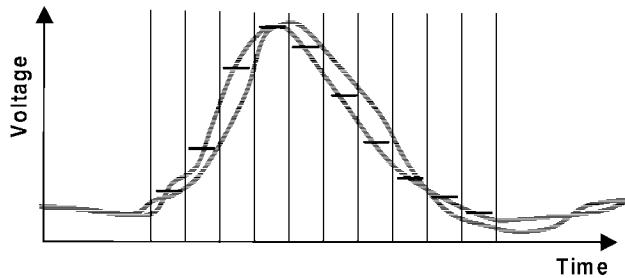
with increasing hearing instrument gain in one infant (Case H) with bilateral severe sensorineural hearing loss who was initially given insufficient gain as it was assumed that his toneburst ABR thresholds overestimated his hearing loss. When he was old enough for behavioral testing at seven months, the results agreed closely with thresholds predicted by his original toneburst ABR, his hearing instrument gain was increased, and there was a substantial improvement in his speech-evoked aided CAEP.

## Statistical Analysis of CAEP Waveforms

Traditionally AEP waveforms are characterised by identifying the latencies and amplitudes of the

main peaks in the waveform (e.g., wave V of the ABR) and comparing these to normative values. In research, analyses of variance can be performed to see whether group evoked potential data show significant differences between stimuli, populations (normal hearing versus hearing impaired), aided and unaided conditions, and with changes in hearing instrument parameters. This approach is not relevant for clinical applications, however. One solution to the problem of determining whether waveforms are present and differ between stimulus or hearing aid conditions for an individual child is illustrated in figure 5. The CAEP waveform is divided into a series of time bins in the region of interest, and average voltages are computed for each time bin and each recording epoch. Since approximately 100 to 200 epochs are recorded for





**Figure 5.** Illustration of the Multivariate Analysis of Variance (MANOVA) technique for determining if there are significant differences in CAEP waveforms obtained from the same infant for different stimuli. The waveform is divided into multiple time bins in the region of interest and the average voltage is computed for each time bin. The result is the probability that the two waveforms come from different statistical distributions.

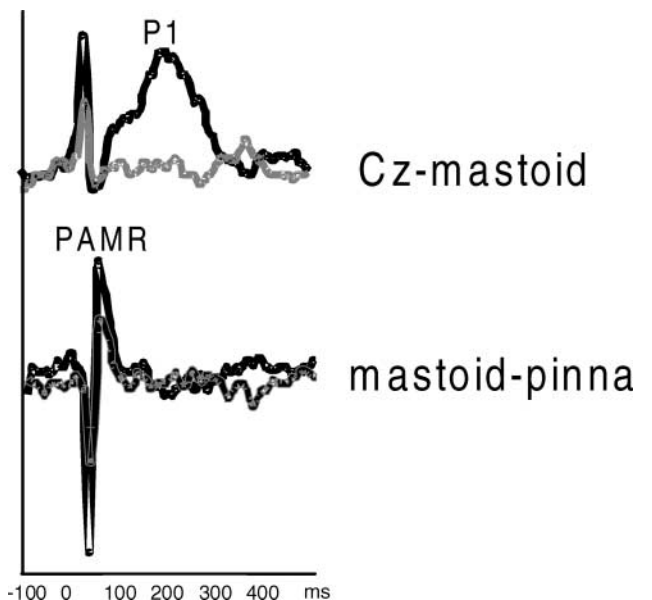
each condition (stimulus type, hearing instrument setting), this process generates a large number of time-varying voltages for each child. These voltages can be compared across conditions for individual children using multivariate analysis of variance (MANOVA). We have found that, using the MANOVA approach, all infants with normal hearing ( $n=20$ ) have significantly different cortical responses to two very different speech stimuli [t] and [m], and that about a half of the infants have different responses to the more similar speech sounds [t] and [g]. In the MANOVA analysis the region of interest is chosen so that the early portion of the waveform, that contains PAMR for some stimuli, is excluded to ensure that only the CAEP peaks are compared.

### Practical Suggestions for Successful CAEP Recordings in Infants

Because infants need to be settled and awake for the CAEP testing, the timing of appointments and having a test setup that is comfortable for mothers and infants is very important. Successful distraction of the infant is a crucial factor. If the infant is too active, the recordings will take too long and/or will contain too much muscle activity. A wide range of quiet, visually engaging distraction items (toys, books, mirrors, hand-held lights) are needed to maintain the interest of the infant throughout what can be a lengthy test session. Individual test runs last several minutes and should be paused if the infant is too vocal. The infant's state needs to be closely monitored as they will occasionally fall asleep unexpectedly or

can be close to sleep with their eyes open. Figure 6 shows an example of successive [t]-evoked CAEP waveforms recorded from a young infant with normal hearing who fell asleep between test runs. Although there were only a few minutes between the recordings, the first recording shows a robust CAEP waveform and the next shows an absent CAEP when the infant fell asleep. Interestingly the recorded waveform still contains the early post-auricular muscle response (PAMR) that is a brainstem response (Gibson 1978) and is less affected by sleep than the CAEP in this example.

Electrode application needs to be fast, painless, and secure since the infant will probably be sitting up on a caregiver's lap and will be awake during recordings. This is in contrast with the situation audiologists are more familiar with, when infants are asleep and supine for ABR or ASSR recordings. It is advisable to ask families not to use cream or hair



**Figure 6.** Evoked potential recording in a 3-month infant with normal hearing in response to a [t] speech stimulus at 65 dB SPL (average of 100 stimulus presentations after artifact rejection at  $\pm 100 \mu\text{V}$ , 750 ms inter-stimulus interval), for two different electrode montages. The dark and light lines show the responses recorded immediately before and after the infant fell asleep, respectively. The post-auricular muscle response (PAMR) is only slightly reduced in amplitude during sleep in this case, but the CAEP (P1) disappears. Note that the PAMR is inverted and enhanced in amplitude when recorded with the non-inverting electrode on the mastoid and the inverting electrode on the back of the pinna, compared to the vertex recording. The mastoid-pinna recording montage is optimal for recording PAMR only (O'Beirne and Patuzzi 1999).

conditioner on the infant's head prior to coming to the appointment as the electrodes can slide off as a result. Wet gel electrodes (Eggins 1993) will generally remain secure throughout the test session but can be problematic if hair prevents a secure contact with the scalp, in which case it may be necessary to use conventional surface electrodes and tape. Electrodes need to be draped away from the face and the hands so that they are less likely to be noticed and pulled at by the infant. A lanolin-based cream should be used to assist in electrode removal so that this is not distressing for the awake infant. If the infant is still happy being distracted, test sessions can be quite long, especially if two ears are tested with and without hearing instruments and with a range of speech stimuli. Frequent monitoring of electrode impedances to ensure they are optimal is recommended. The distractor and caregiver should monitor the electrodes to ensure they remain secure throughout testing. For aided testing it is wise to ensure the hearing instruments have new batteries at the start of the session.

CAEP peaks can be absent, reduced in amplitude, have prolonged latencies or have unusual morphology, which can make waveform identification difficult. Both unaided and aided responses should be recorded with several replications to ensure that CAEP peaks can be reliably identified. We have, however, also successfully applied MANOVA to the task of detecting the presence of a CAEP. The availability of such a technique, which will be described elsewhere, then makes it possible for clinicians with limited electrophysiological experience to use CAEPs to evaluate aided functioning, with only a single recording run per speech sound evaluated.

The major goal of aided CAEP evaluation is to ensure that the child has access to conversational level speech and hence stimulus levels of 65 dB SPL are recommended. Louder levels may be required, however, in order to identify a CAEP waveform if responses are poor. If aided testing is conducted with high stimulus levels, care should be used to ensure that the hearing instrument is not saturated. Lower levels, such as 55 dB SPL, can also be used to evaluate whether the hearing aid fitting is giving the infant access to the speech sounds present in softer speech.

## Conclusions

CAEPs can be used to determine the audibility of speech sounds, aided or unaided, for clients who can-

not respond reliably for behavioral testing, such as infants and children with developmental delay. The results of aided CAEP testing may suggest the need to consider alternative management. For example, if very poor responses are present and a profoundly deaf infant is already wearing high-powered hearing instruments, this may expedite the decision to proceed with cochlear implant candidacy evaluation or the use of alternative communication modalities such as sign. The idea that CAEPs can be used to guide the fine tuning of hearing instruments is reasonable, but is yet to be fully validated. A simple approach to using the CAEPs to guide hearing instrument fitting is to increase low-frequency gain if the CAEP evoked by a low-frequency speech stimulus such as [m] is absent, or to increase high-frequency gain if the CAEP evoked by a high-frequency speech stimulus such as [t] is absent. This technique *cannot* indicate excessive hearing instrument gain, but this may be possible in the future as we learn more about the input-output characteristics of CAEP in infants with normal hearing. Future research will assess hearing instrument performance using both behavioral and CAEP measures in the same children to cross-validate the methods, and will determine the sensitivity of CAEP recordings to hearing instrument fine-tuning adjustments.

## Acknowledgements

This research was supported by the Australian Cooperative Research Centre for Cochlear Implant and Hearing Aid Innovation. The support of Gladesville Baby Health Centre, the Australian Hearing Centres, the Royal Institute for Deaf and Blind Children, Sydney Cochlear Implant Centre, and The Deafness Centre, Children's Hospital at Westmead is gratefully acknowledged.

## References

- Agung, K.B., Purdy, S.C., Patuzzi, R.B., O'Beirne, G.A., and Newall, P. in press. Rising-frequency chirps and earphones with an extended high frequency response enhance the post-auricular muscle response. *International Journal of Audiology*.
- Alcantara, J.L., Moore, B.C., Kuhnel, V., and Launer, S. 2003. Evaluation of the noise reduction system in a commercial digital hearing aid. *International Journal of Audiology* 42(1):34–42.

- Bahls, F.H., Chatrian, G.E., Mesher, R.A., Sumi, S.M., and Ruff, R.L. 1988. A case of persistent cortical deafness: Clinical, neurophysiologic, and neuropathologic observations. *Neurology* 38(9):1490–1493.
- Beauchaine, K.A., Gorga, M.P., Reiland, J.K., and Larson, L.L. 1986. Application of ABRs to the hearing aid selection process: Preliminary data. *Journal of Speech and Hearing Research* 29(1):120–128.
- Bergman, B.M., Beauchaine, K.L., and Gorga, M.P. 1992. Application of the auditory brainstem response in pediatric audiology. *Hearing Journal* 45:19–21, 24–25.
- Brown, E., Klein, A.J., and Snyder, K.A. 1999. Hearing-aid-processed tone pips: Electroacoustic and ABR characteristics. *Journal of the American Academy of Audiology* 10:190–197.
- Byrne, D. 1986. Effects of frequency response characteristics on speech discrimination and perceived intelligibility and pleasantness of speech for hearing-impaired listeners. *Journal of the Acoustical Society of America* 80(2):494–504.
- Byrne, D., Dillon, H., Ching, T., Katsch, R., Keidser, G. 2001. NAL-NL1 procedure for fitting nonlinear hearing aids: characteristics and comparisons with other procedures. *Journal of the American Academy of Audiology* 12(1): 37–51.
- Ching, T.Y., and Dillon, H. 2003. Prescribing amplification for children: Adult-equivalent hearing loss, real-ear aided gain, and NAL-NL1. *Trends in Amplification* 7(1):1–9.
- Cody, D.T.R., Klass, D.W., and Bickford, R.G. 1967. Cortical audiometry: An objective method of evaluating auditory acuity in awake and sleeping man. *Transactions American Academy of Ophthalmology and Otolaryngology* 71:81–91.
- Cone-Wesson, B. 2003. Pediatric audiology: A review of assessment methods for infants. *Audiological Medicine* 1(3):175–184.
- Cunningham, J., Nicol, T., Zecker, S., and Kraus, N. 2000. Speech-evoked neurophysiologic responses in children with learning problems: development and behavioral correlates of perception. *Ear and Hearing* 21(6):554–568.
- Dalebout, S.D., and Robey, R.R. 1997. Comparison of the intersubject and intrasubject variability of exogenous and endogenous auditory evoked potentials. *Journal of the American Academy of Audiology* 8(5):342–354.
- Davidson, S.A., Wall, L.G., and Goodman, C.M. 1990. Preliminary studies on the use of an ABR amplitude projection procedure for hearing aid selection. *Ear and Hearing* 11(5):332–339.
- Davis, H. 1965. Slow cortical responses evoked by acoustic stimuli. *Acta Oto-laryngologica* Suppl. 206:128–134.
- Dimitrijevic, A., John, M.S., and Picton, T.W. 2004. Auditory steady-state responses and word recognition scores in normal-hearing and hearing-impaired adults. *Ear and Hearing* 25(1):68–84.
- Eggins, B.R. 1993. Skin contact electrodes for medical applications. *Analyst* 118(4):439–442.
- Gerling, I.J. 1991. In search of a stringent methodology for using ABR audiometric results. *Hearing Journal* 44:26, 28–30.
- Gibson, W.P.R. 1978. *Essentials of clinical electric response audiometry*. Edinburgh: Churchill Livingstone.
- Gorga, M.P., Beauchaine, K.A., and Reiland, J.K. 1987. Comparison of onset and steady-state responses of hearing aids: Implications for use of the auditory brainstem response in the selection of hearing aids. *Journal of Speech and Hearing Research* 30(1):130–136.
- Gravel, J., Kurtzberg, D., Stapells, D.R., Vaughan, H.G., and Wallace, I.F. 1989. Case studies. *Seminars in Hearing* 10:272–287.
- Hall, J.W. III. 1992. *Handbook of auditory evoked responses*. Needham Heights, MA: Allyn and Bacon.
- Harrison M. 2000. How do we know we've got it right? Observing performance with amplification. In R.C. Seewald (ed.), *A sound foundation through early amplification: Proceedings of an international conference*. Stäfa, Switzerland: Phonak AG.
- Hecox, K.E. 1983. Role of the auditory brain stem response in the selection of hearing aids. *Ear and Hearing* 4(1):51–55.
- Herdman, A.T., Lins, O., Van Roon, P., Stapells, D.R., Scherg, M., and Picton, T. W. 2002. Intracerebral sources of human auditory steady-state responses. *Brain Topography* 15(2):69–86.
- Hood, L.J., Berlin, C.I., and Allen, P. 1994. Cortical deafness: A longitudinal study. *Journal of the American Academy of Audiology* 5(5):330–342.
- Houston, D.M., Pisoni, D.B., Kirk, K.I., Ying, E.A., and Miyamoto, R.T. 2003. Speech perception skills of deaf infants following cochlear implantation: A first report. *International Journal of Pediatric Otorhinolaryngology* 67(5):479–495.
- Hyde, M. 1997. The N1 response and its applications. *Audiology Neuro-otology* 2(5):281–307.
- Kiessling, J. 1982. Hearing aid selection by brainstem audiometry. *Scandinavian Audiology* 11(4):269–275.
- Kileny, P. 1982. Auditory brainstem responses as indicators of hearing aid performance. *Annals of Otology* 91(1 Pt 1):61–64.

- Kraus, N., and Cheour, M. 2000. Speech sound representation in the brain. *Audiology Neuro-otology* 5(3-4):140-150.
- Kraus, N., Koch, D.B., McGee, T.J., Nicol, T.G., and Cunningham, J. 1999. Speech-sound discrimination in school-age children: Psychophysical and neurophysiologic measures. *Journal of Speech Language Hearing Research* 42(5):1042-1060.
- Kraus, N., and McGee, T. 1993. Clinical implications of primary and nonprimary pathway contributions to the middle latency response generating system. *Ear and Hearing* 14(1):36-48.
- Kurtzberg, D., Hilpert, P.L., Kreuzer, J.A., and Vaughan, H.G. Jr. 1984. Differential maturation of cortical auditory evoked potentials to speech sounds in normal full-term and very low-birthweight infants. *Developmental Medicine and Child Neurology* 26(4):466-475.
- Kushnerenko, E., Èeponienë, R., Balan, P., Fellman, V., Huotilainen, and Näätänen, R. 2002. Maturation of the auditory event-related potentials during the first year of life. *Neuroreport* 13(1):47-51.
- Leijon, A., Lindkvist, A., Ringdahl, A., Israelsson, B. 1990. Preferred hearing aid gain in everyday use after prescriptive fitting. *Ear and Hearing* 11(4):299-305.
- Mahoney, T.M. 1985. Auditory brainstem response hearing aid applications. In J.T. Jacobson (ed.), *The auditory brainstem response*. Boston: College-Hill.
- McGee, T., and Kraus, N. 1996. Auditory development reflected by middle latency response. *Ear and Hearing* 17(5):419-429.
- Näätänen, R., Pakarinen, S., Rinne, T., and Takegata, R. 2004. The mismatch negativity (MMN): Towards the optimal paradigm. *Clinical Neurophysiology* 115(1):140-144.
- Novak, G.P., Kurtzberg, D., Kreuzer, J.A., and Vaughan, H.G. Jr. 1989. Cortical responses to speech sounds and their formants in normal infants: Maturational sequence and spatiotemporal analysis. *Electroencephalography and Clinical Neurophysiology* 73(4):295-305.
- Oates, P.A., Kurtzberg, D., and Stapells, D.R. 2002. Effects of sensorineural hearing loss on cortical event-related potential and behavioral measures of speech-sound processing. *Ear Hearing* 23(5):399-415.
- O'Beirne, G.A., and Patuzzi, R.B. 1999. Basic properties of the sound-evoked post-auricular muscle response (PAMR). *Hearing Research* 138(1-2):115-132.
- Pasman, J.W., Rotteveel, J.J., de Graaf, R., Maassen, B., and Notermans, S.L.H. 1991. Detectability of auditory evoked response components in preterm infants. *Early Human Development* 26(2):129-141.
- Patuzzi, R.B., and Thomson, S.M. 2000. Auditory evoked response test strategies to reduce cost and increase efficiency: The postauricular muscle response revisited. *Audiology Neuro-otology* 5(6):322-332.
- Picton, T.W., Alain, C., Otten, L., Ritter, W., and Achim, A. 2000. Mismatch negativity: different water in the same river. *Audiology and Neuro-otology* 5(3-4):111-139.
- Picton, T.W., Durieux-Smith, A., Champagne, S.C., Whittingham, J., Moran, L.M., Giguere, C., and Beauguard, Y. 1998. Objective evaluation of aided thresholds using auditory steady-state responses. *Journal of the American Academy of Audiology* 9(5):315-331.
- Ponton, C.W., Don, M., Eggermont, J.J., Waring, M.D., and Masuda, A. 1996. Maturation of human cortical auditory function: Differences between normal-hearing children and children with cochlear implants. *Ear and Hearing* 17(5):430-437.
- Ponton, C.W., Eggermont, J.J., Kwong, B., and Don, M. 2000. Maturation of human central auditory system activity: Evidence from multi-channel evoked potentials. *Clinical Neurophysiology* 111(2):220-236.
- Purdy, S.C., Katsch, R.K., Storey, L.M., Dillon, H., and Ching, T.Y. 2001. Slow cortical auditory evoked potentials to tonal and speech stimuli in infants and adults. Paper presented at the 17th International Evoked Response Audiometry Study Group Biennial Symposium, Vancouver, Canada.
- Purdy, S.C., Sharma, M., Katsch, R., Storey, L., Dillon H., and Ching, T.Y. 2003. Obligatory cortical responses in normal hearing infants and use of aided cortical responses to assess hearing aid function in infants and children with hearing impairment. Paper presented at the 18th Biennial International Evoked Response Audiometry Study Group, Puerto de la Cruz, Spain.
- Rance, G., Cone-Wesson, B., Wunderlich, J., and Dowell, R. 2002. Speech perception and cortical event related potentials in children with auditory neuropathy. *Ear and Hearing* 23(3):239-253.
- Rapin, I., and Graziani, L.J. 1967. Auditory-evoked responses in normal, brain-damaged, and deaf infants. *Neurology* 17(9):881-894.
- Rickards, F.W., and De Vidi, S. 1995. Exaggerated hearing loss in noise induced hearing loss compensation claims in Victoria. *Medical Journal of Australia* 163(7):360-363.
- Seewald, R.C., Moodie, K.S., Sinclair, S.T., and Scollie,

- S.D. 1999. Predictive validity of a procedure for pediatric hearing instrument fitting. *American Journal of Audiology* 8(2):143–152.
- Seewald, R.C., and Scollie S.D. 2003. An approach for ensuring accuracy in pediatric hearing instrument fitting. *Trends in Amplification* 7(1):29–40.
- Scollie, S.D., Seewald, R.C., Cornelisse, L.E., and Jenstad, L.M. 1998. Validity and repeatability of level-independent HL to SPL transforms. *Ear and Hearing* 19(5):407–413.
- Sharma, A., Dorman, M.F., and Spahr, A.J. 2002. A sensitive period for the development of the central auditory system in children with cochlear implants: Implications for age of implantation. *Ear and Hearing* 23(6):532–539.
- Sharma, A., Kraus, N., McGee, T.J., and Nicol, T.G. 1997. Developmental changes in P1 and N1 central auditory response elicited by consonant-vowel syllables. *Electroencephalography and Clinical Neurophysiology* 104(6):540–545.
- Sharma M., Purdy S.C., Newall P., Wheldall K., Beaman R., Dillon H. 2004. Effects of identification technique, extraction method, and stimulus type on mismatch negativity in adults and children. *Journal of the American Academy of Audiology* 15(9):616–632.
- Snik, A.F.M., and Stollman, M.H.P. 2000. Fitting pre-school and primary school children with hearing aids: An evaluation of hearing aid prescription rules. In R.C. Seewald (ed.), *A sound foundation through early amplification: Proceedings of an international conference*. Stäfa, Switzerland: Phonak AG.
- Stapells, D.R. 2002. Cortical event-related potentials to auditory stimuli. In J. Katz (ed.), *Handbook of Clinical Audiology* (Fifth Edition). Baltimore, MD: Williams and Wilkins.
- Tharpe, A.M., Sladen, D., Huta, H.M., and McKinley Rothpletz, A. 2001. Practical considerations of real-ear-to-coupler difference measures in infants. *American Journal of Audiology* 10(1):41–49.
- Tremblay, K.L., Friesen, L., Martin, B.A., and Wright, R., 2003. Test-retest reliability of cortical evoked potentials using naturally produced speech sounds. *Ear and Hearing* 24(3):225–232.
- Tremblay, K.L., and Kraus N. 2002. Auditory training induces asymmetrical changes in cortical neural activity. *Journal of Speech, Language and Hearing Research* 45(3):564–572.
- Tsu, B., Wong, L.L., and Wong, E.C., 2002. Accuracy of cortical evoked response audiometry in the identification of non-organic hearing loss. *International Journal of Audiology* 41(6):330–333.
- Werker, J.F. and Tees R.C. 2002. Cross-language speech perception: Evidence for perceptual reorganization during the first year of life. *Infant Behavior and Development* 25(1):121–133.
- Yoshinaga-Itano, C. 2003. Early intervention after universal neonatal hearing screening: Impact on outcomes. *Mental Retardation Developmental Disabilities Research Reviews* 9(4):252–266.
- Yoshinaga-Itano, C. 2004. Levels of evidence: universal newborn hearing screening (UNHS) and early hearing detection and intervention systems (EHDI). *Journal of Communication Disorders* 37(5): 451–465.
- Yoshinaga-Itano, C., Sedey, A.L., Coulter, D.K., and Mehl, A.L. 1998. Language of early- and later-identified children with hearing loss. *Pediatrics* 102(5): 1161–1171.

