Prediction of Hearing Threshold in Infants Using Auditory Steady-State Evoked Potentials

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Abstract

This retrospective study examines the relationship between auditory steady-state evoked potential (ASSEP) thresholds determined in infancy and subsequently obtained behavioral hearing levels in children with normal hearing or varying degrees of sensorineural hearing loss. Overall, the results from 211 subjects showed that the two test techniques were highly correlated, with Pearson r values exceeding .95 at each of the audiometric test frequencies between 500 and 4000 Hz. Analysis of the findings for babies with significant hearing loss (moderate to profound levels) showed similar threshold relationships to those obtained in previous studies involving adults and older children. The results for infants with normal or near-normal hearing did, however, differ from those reported for older subjects, with behavioral thresholds typically 10 to 15 dB better than would have been predicted from their ASSEP levels.

Key Words: Auditory steady-state evoked potentials, hearing, infants

Abbreviations: ABR = auditory brainstem response; AM = amplitude modulation; ASSEP = auditory steady-state evoked potentials; FM = frequency modulation

Sumario

Este estudio retrospectivo examina la relación entre los umbrales para potenciales evocados auditivos de estado-estable (ASSEP) determinados en la infancia, con niveles auditivos conductuales obtenidos subsecuentemente en niños con audición normal y con grados variables de hipoacusias sensorineurales. Globalmente, los resultados de 211 sujetos mostraron que las dos técnicas de evaluación correlacionaron fuertemente, con valores r de Pearson por encima de .95 en las frecuencias audiométricas entre 500 y 4000 Hz. El análisis de los hallazgos en bebés con hipoacusia significativa (niveles moderados a profundos) mostró umbrales relacionados similares a los obtenidos en nuestros previos estudios involucrando adultos y niños mayores. Los resultados de niños con audición normal o cercana a la normalidad difirió, sin embargo, de aquellos reportados para sujetos mayores, con umbrales conductuales típicamente 10 a 15 dB mejores de lo que hubiera sido esperado de sus niveles con ASSEP.

Palabras Clave: Potenciales evocados auditivos de estado-estable, audición, infantes

Abreviaturas: ABR = respuestas auditivas del tallo cerebral; AM = modulación de la amplitud; ASSEP = potenciales auditivos evocados de estado estable; FM = modulación de la frecuencia

The link between infant hearing loss and speech and language deficits is well established. So, too, are the ameliorating effects of early diagnosis and intervention (Markides 1986; Levitt and McGarr, 1988; Ramkalawan and Davis, 1992). Recent studies by Yoshinaga-Itano and colleagues (1998) and Moeller (2000) have shown that hearing-impaired children who are amplified and who receive educational support in the first 6 months of life have significantly greater potential for speech and language development than do children receiving intervention

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at a later age. The challenge, then, for hearing professionals is to identify affected babies during this critical period and to produce audiometric profiles that are detailed enough to provide a basis for intervention.

The limitations of behavioral audiometric testing in children less than 6 months of age have generated a great deal of research interest in techniques that do not require volitional responses. The auditory steady-state evoked potential (ASSEP) procedure is one such method that has proven useful over the past decade. ASSEPs are continuous scalp-recorded potentials that arise in response to periodically time-varying stimuli such as amplitude- and frequency-modulated tones (Rickards and Clark, 1984; Kuwada et al, 1986). The response is a complex periodic wave and is phase-locked to the modulation envelope of the stimulus. ASSEPs can be elicited by a wide range of modulation frequencies, but rates around 70 to 100 Hz have been most effective for infant testing. The resulting potential has an equivalent latency of approximately 10 msec, suggesting late brainstem generators (Cohen et al, 1991; Aoyagi et al, 1993; Levi et al, 1993; Lins and Picton, 1995), and, like the transient auditory brainstem response (ABR), is relatively unaffected by subject state (sleep/sedation) (Cohen et al, 1991; Levi et al, 1993; Rance et al, 1995) and is reliably present in children of all ages (Aoyagi et al, 1993; Rickards et al, 1994; Lins et al, 1996). Rickards and colleagues (1994) demonstrated that high modulation rate ASSEP testing in normal neonates could elicit responses at reasonably low presentation levels. These authors found mean threshold levels at 41, 24, and 34 dB HL for the 500-, 1500-, and 4000-Hz carrier frequencies.

ASSEPs have also been investigated in studies involving adults and children with varying degrees of hearing loss. ASSEP thresholds in these subjects have generally been highly correlated to behavioral hearing level, particularly in cases of significant sensorineural loss in which recruitment effects have produced thresholds at low (~ 5–10 dB) sensation levels (Rance et al, 1995, 1998; Lins et al, 1996; Aoyagi et al, 1999; Johnson and Brown, 2001). Furthermore, evoked potential "audiograms" based on the ASSEP thresholds obtained in these subjects have consistently mirrored both the degree and configuration of the losses.

In our recent study (Rance and Briggs, 2002), we examined the reliability of ASSEP threshold testing in a group of babies with sig-

nificant hearing loss. This retrospective analysis compared ASSEP levels obtained in infancy (mean age at assessment = 3 months) with subsequently obtained behavioral hearing thresholds and showed a strong correlation between test techniques. As such, the data indicated that ASSEP thresholds could be used as a basis for hearing aid fitting in babies with sensorineural hearing loss.

This study further investigates the relationship between ASSEP and behavioral hearing thresholds in a group of infants with normal hearing and varying degrees of sensorineural loss. In particular, we examine how accurately the Rance and colleagues' (1995) prediction formulae (which were based on ASSEP/behavioral threshold correlation data from adults and young children) estimated hearing threshold in these babies.

METHOD

Subjects

This retrospective study presents the clinical findings obtained at The University of Melbourne, School of Audiology Clinic for 211 infants aged 1 to 8 months (mean age = 3.2 months) at the time of ASSEP assessment. In most cases, the children were referred for ASSEP testing following failure on a click-evoked ABR screening assessment (ABR threshold > 40 dB nHL in both ears).

Subjects were included only if they showed no evidence of middle ear pathology (normal multiple probe tone tympanometric results and normal otoscopy) on each of the test occasions and if their ABR assessment showed no evidence of neural transmission disorder (auditory neuropathy) (Rance et al 1999; Rance and Briggs, 2002). Children with deteriorating hearing loss (confirmed by repeat behavioral and evoked potential assessments) were also excluded.

Apparatus and Procedures

Behavioral Testing

The behavioral audiogram was established for each ear in a double-walled, sound-attenuating room. Testing was carried out under headphones or tubephones using conditioned audiometric techniques (visual response audiometry) and the 10 dB down, 5 dB up threshold

search procedure. A clinical audiometer (Madsen OB822) was used to generate warble tones at octave frequencies ranging from 500 to 4000 Hz.

The age at which the children were mature enough to complete the audiometric testing ranged from 6 to 14 months (mean age = 7.9 months). As such, there was typically a delay of approximately 6 months between the time of the evoked potential and audiometric testing.

Evoked Potential Testing

ASSEP assessment was also performed in a sound-treated room using an IBM-compatible XT-type microcomputer to generate stimuli and analyze responses in the manner described by Cohen and colleagues (1991). The subjects were nursed by a parent and were in natural sleep throughout the testing. Electroencephalographic (EEG) activity was monitored using silver-silver chloride disk electrodes placed on the high forehead (+ve) and on the earlobe or mastoid ipsilateral to the stimulated ear (−ve). A similar electrode was placed on the contralateral earlobe or mastoid to act as a ground. The subjects' skin was lightly abraded at the electrode site using a mixture of pumice powder and electrode paste. Preparation in this manner produced interelectrode impedances of less than 10 kohms at 260 Hz. The raw EEG was passed through a preamplifier and filtered using a bandpass of 0.2 to 10 kHz. Samples were rejected if the amplitude exceeded 0.5 μV (peak to peak). This value was determined as described in Cohen and colleagues (1991).

Fourier analysis of the EEG signal was performed at the stimulus modulation frequency (90 Hz) using analog multiplication followed by low-pass filtering (Regan, 1966). Two multipliers and two low-pass filters were employed to extract both ASSEP phase and amplitude information. The output of these filers was sampled after every 30-second modulation period. The presence or absence of a response was determined automatically from these data using a statistical detection criterion based on nonrandom phase behavior (phase coherence) (Jerger et al, 1986; Cohen et al, 1991). The system calculated the probability that a set of independent phase angles could arise in the absence of a response (i.e., be the result of random EEG activity). If the probability of this occurring was sufficiently small (p < .01) over a given period (10% of the total running time), a response was considered to be present and the run was ended. A minimum of 60 samples was required before a run could be accepted, and the response was considered absent if the statistical criterion had not been met after 256 samples. As such, the time taken for each run ranged from approximately 20 to 90 seconds.

The test stimuli were continuous 500-, 1000-, 2000-, and 4000-Hz tones amplitude and frequency modulated at a rate of 90 Hz. An amplitude modulation (AM) depth of 100 percent and a frequency modulation (FM) width of 10 percent were combined to maximize response amplitude (Cohen et al, 1991). Modulation width was defined as $100 \times (F_{max} - F_{min})/F_{carrier}$. The degree of frequency modulation was limited to 10 percent so that the energy spectra of the stimuli were essentially contained within one critical bandwidth.

The stimuli were presented via Etymotic Research ER-3A tubephones with foam earplugs, or mu-metal shielded TDH-39 headphones that allowed maximum presentation levels of 120 dB HL. Calibration was performed using pure tones as per the Australian Standard 1591.2, a Bruel and Kjaer 2613 amplifier, and a Bruel and Kjaer 2120 frequency analyzer. The introduction of FM did not alter the peak-to-peak amplitude of the stimuli. AM did produce a slight change in stimulus energy (≤ 2 dB), which was confirmed in behavioral testing with a group of 10 normal-hearing adults and allowed for in the system calibration.

ASSEP thresholds were obtained using a 10 dB down, 5 dB up search procedure with a starting level of approximately 60 dB HL. Threshold was defined as the minimum level at which the phase coherence was statistically significant. On occasions for which no ASSEP could be identified at maximum presentation levels, the run was repeated. Testing was carried out for each of the subjects in this way using stimuli presented monaurally at a range of carrier frequencies. In most cases, thresholds for the four test stimuli could be established in both ears within a 45- to 60-minute test period. Clinical constraints did, however, mean that not all of the test frequencies could be assessed for every child.

RESULTS

Figure 1 shows the relation between the ASSEP and behavioral hearing thresholds obtained at each test frequency for all of the ears tested (n = 405). A total of 809 comparisons were made. Of these, 272 were at 500 Hz, 260 were at 1000 Hz, 140 were at 2000 Hz, and 137 were at 4000 Hz. Instances in which either
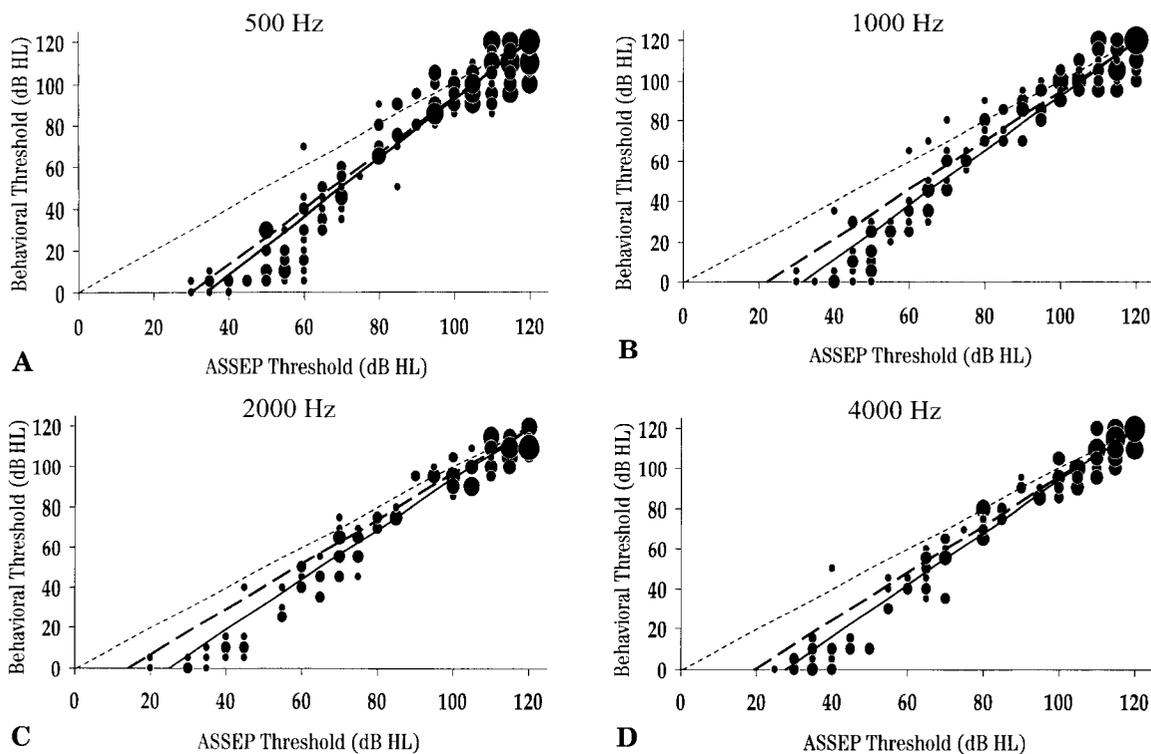
Figure 1 The distribution of auditory steady-state evoked potential (ASSEP)/behavioral threshold comparisons. Multiple data points falling at a particular coordinate are represented by a single icon. The total number of ears varied with test frequency: 500 Hz, 272; 1000 Hz, 260; 2000 Hz, 140; 4000 Hz, 137. The *solid lines* are the lines of best fit for each frequency. The *dashed lines* are the regression lines from Rance and colleagues (1995).

the ASSEP or behavioral thresholds were absent at maximum presentation levels (n = 517) were not included in the correlation analyses and are addressed separately.

Overall, the data show a strong relationship between ASSEP thresholds established in infancy and subsequently obtained hearing levels for these young children. The correlation coefficient value for each of the test frequencies was ≥ .96, and the overall Pearson r value was 0.97 (Table 1).

The linear regression lines fitted to the data in Figure 1 (solid lines) were similar to those

obtained in our previous study involving adults and older children (Rance et al, 1995). As with the previous investigation, the regression slopes of greater than unity reflect the fact that ASSEP thresholds are closer to behavioral hearing levels in ears with greater degrees of hearing loss. The regression lines from the Rance and colleagues' (1995) article (which employed identical ASSEP test procedures) are also included in Figure 1 (dashed lines), and the regression formulae from both studies are presented in Table 2. One consistent difference between the two sets of formulae is that the x-intercept values for

Table 1 Pearson Product-Moment Coefficient Values Showing the Correlation between ASSEP and Behavioral Thresholds for Each of the Test Frequencies

	Frequency (Hz)			
	500	*1000*	*2000*	*4000*
Pearson r	.96	.97	.98	.97

ASSEP = auditory steady-state evoked potential.

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Table 2   Linear Regression Formulae for the Distribution of ASSEP/Behavioral Hearing Threshold Comparisons

Frequency (Hz)	1995	2002
500	y = 1.29x − 40.1	y = 1.39x − 49.0
1000	y = 1.18x − 25.5	y = 1.35x − 44.3
2000	y = 1.14x − 19.5	y = 1.28x − 35.6
4000	y = 1.19x − 23.6	y = 1.31x − 38.8

Based on the authors' data and the data presented in Rance and colleagues (1995).

y = predicted behavioral threshold; x = auditory steady-state evoked potential (ASSEP) threshold.
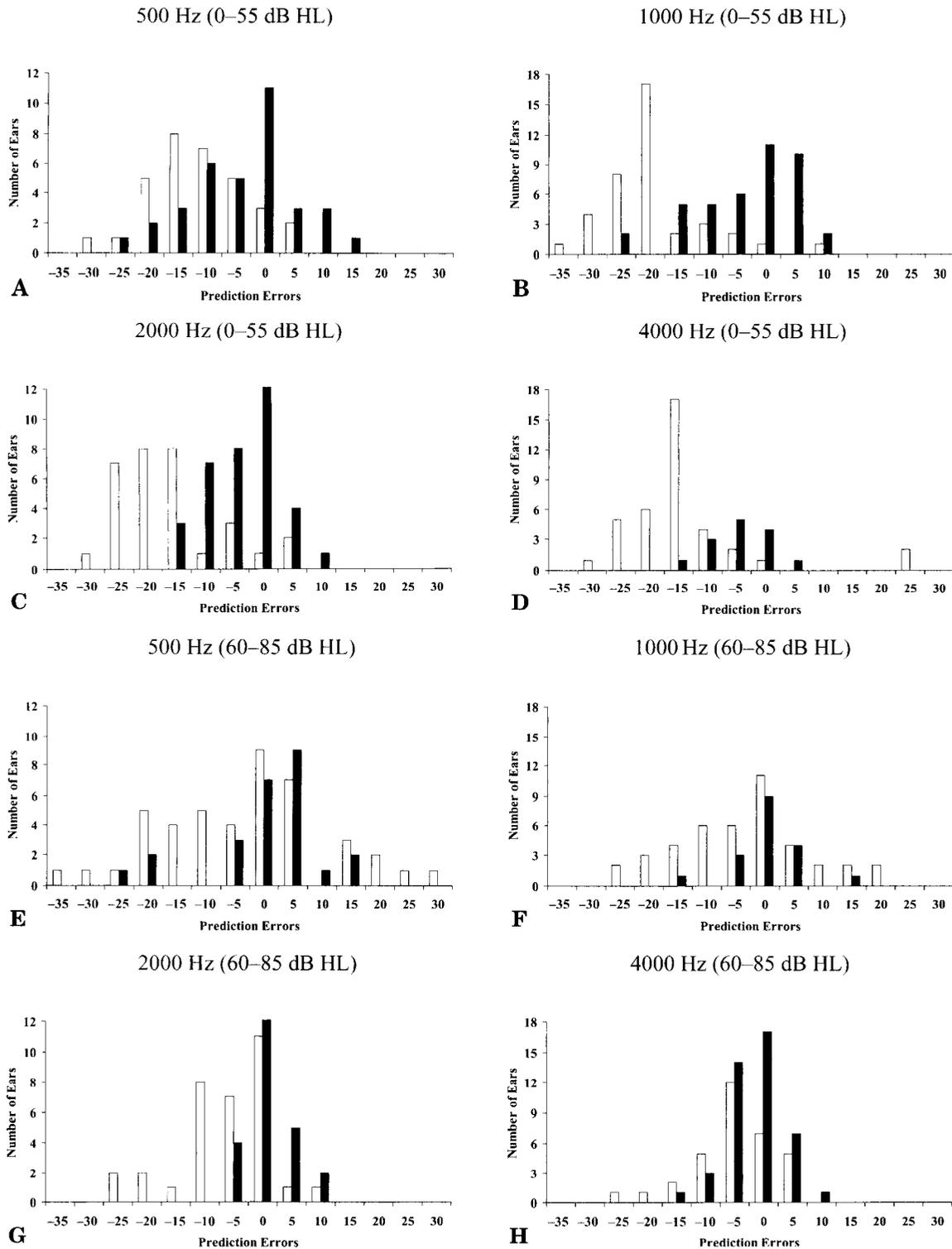
Table 3   Mean and Standard Deviation Values (dB) of the Prediction Errors for the Current Data Set (Infants) and the Rance and Colleagues' (1995) Data (Older Children and Adults)

Hearing Category	Frequency (Hz)			
	500	1000	2000	4000
1995 data				
0–55 dB HL				
n	35	41	36	14
Mean error	−1.23	−1.20	−1.07	−1.49
SD	9.64	8.63	6.29	4.74
60–85 dB HL				
n	25	18	26	43
Mean error	2.49	3.18	2.77	0.42
SD	9.62	5.71	3.89	5.10
90+ dB HL				
n	29	27	22	21
Mean error	−0.60	−0.35	−1.42	0.13
SD	6.18	5.36	3.60	4.70
Total	89	86	84	78
2001 data				
0–55 dB HL				
n	32	39	31	38
Mean error	−8.70	−17.17	−13.43	−11.75
SD	8.57	8.65	8.54	10.78
60–85 dB HL				
n	44	42	33	36
Mean error	−1.04	−1.00	−3.55	−3.02
SD	14.20	10.64	8.29	7.18
90+ dB HL				
n	196	179	76	63
Mean error	1.50	−0.18	−1.08	−2.02
SD	7.76	6.51	6.27	6.30
Total	272	260	140	137

the current study are slightly higher, suggesting that for our infant subjects with normal or near-normal hearing, ASSEP thresholds were usually obtained at higher sensation levels.

To further investigate the relationship between the current findings and those described in the Rance and colleagues (1995) article, "error" values were calculated for each data point. For each case, an estimate of behavioral hearing threshold was calculated from the ASSEP value using the 1995 prediction formulae. The error was defined as the difference between this predicted value and the actual hearing threshold (error = actual − predicted). To evaluate the effect of hearing level on these error values, the data were divided into three categories based on ASSEP level. The groups were defined as follows: category 1, 0 to 55 dB HL; category 2, 60 to 85 dB HL; and category 3, 90+ dB HL.

Figure 2 shows the distribution of error values for each test frequency and each ASSEP category. Table 3 shows the mean and standard deviation of the errors for each group. Comparison of the 1995 and 2002 error sets indicates that for infant ears in ASSEP category 1, a different behavioral/ASSEP threshold relationship exists. For each carrier frequency, ASSEP thresholds were found at higher sensation levels in the infant subjects than in their older counterparts (500 Hz: T_{64} = 3.36, p < .001; 1000 Hz: T_{77} = −8.26, p < .001; 2000 Hz: T_{54} = −6.66, p < .001; 4000 Hz: T_{48} = −4.75, p < .001).

For infants with ASSEP thresholds in categories 2 and 3, the behavioral/ASSEP threshold relationship was more like that seen in older subjects. There were no significant differences between the infant and 1995 error sets at any test frequency for ears in category 3. Similarly, there was no difference between category 2 infant and 1995 groups for the 500- and 1000-Hz carrier frequencies. Small but significant dif-

ferences ($\approx$ 5 dB) were obtained between groups at 2000 and 4000 Hz (2000 Hz: T_{47} = −3.87, p < .001; 4000 Hz: T_{61} = −2.42, p < .02).

These findings are reflected in Figure 3, which shows the ASSEP, predicted behavioral, and actual behavioral thresholds for three typical subjects with varying degrees of sensorineural hearing loss. Although in each of these examples, the ASSEP thresholds mirror the configuration of the behavioral audiogram, the findings for subject A (mild hearing loss) show behavioral thresholds at levels slightly lower than predicted by the 1995 formulae.

Further analysis of the findings for ears in category 1 showed that despite the fact that ASSEP thresholds in babies with normal or near-normal hearing were 10 to 15 dB higher than expected (based on the 1995 data), a clear relationship still existed between ASSEP and behavioral level. Linear regression analyses for

500 Hz (0–55 dB HL)

1000 Hz (0–55 dB HL)

2000 Hz (0–55 dB HL)

4000 Hz (0–55 dB HL)

500 Hz (60–85 dB HL)

1000 Hz (60–85 dB HL)

2000 Hz (60–85 dB HL)

4000 Hz (60–85 dB HL)

Figure 2 Distribution of prediction error values for each carrier frequency and three auditory steady-state evoked potential (ASSEP) level categories. The error value represents the difference between the child's actual hearing threshold and the level predicted from the ASSEP threshold according to the Rance and colleagues (1995) formulae. The *open bars* are the prediction errors for the current (2001) data set (infants), and the *filled bars* show the prediction errors from the 1995 data (adults and older children).
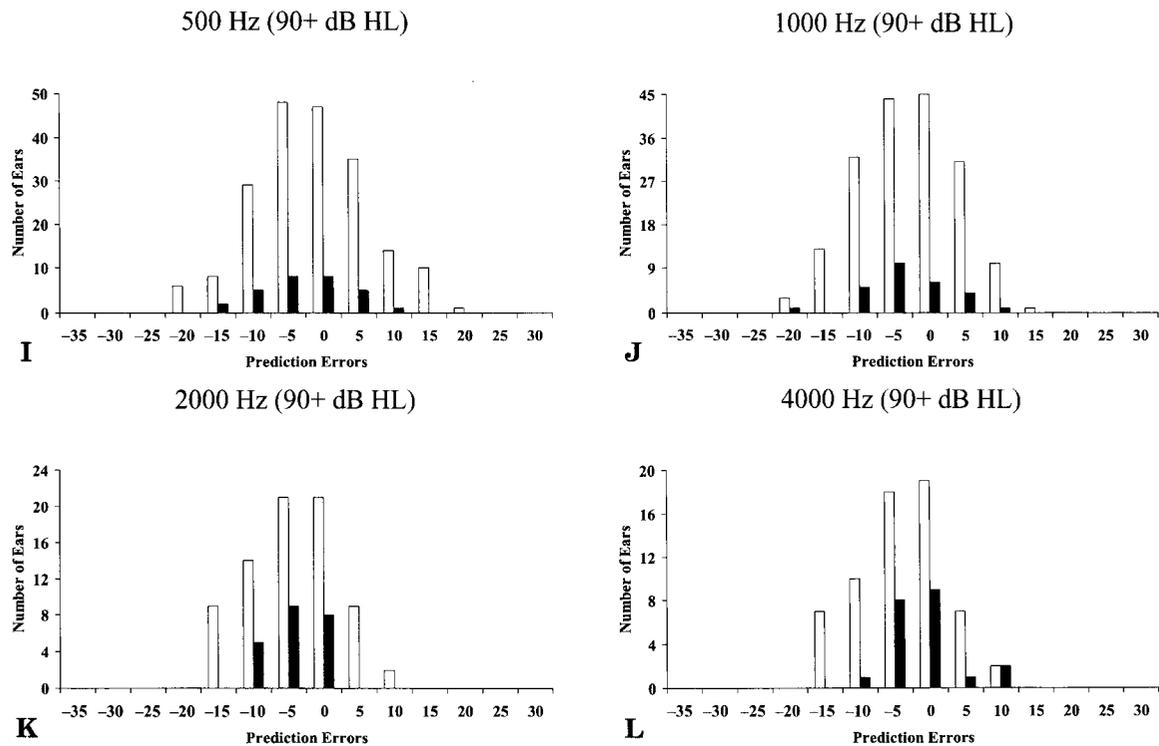
Figure 2 Distribution of prediction error values for each carrier frequency and three auditory steady-state evoked potential (ASSEP) level categories. The error value represents the difference between the child's actual hearing threshold and the level predicted from the auditory steady-state evoked potential (ASSEP) threshold according to the Rance and colleagues (1995) formulae. The *open bars* are the prediction errors for the current (2001) data set (infants), and the *filled bars* show the prediction errors from the 1995 data (adults and older children).

ears with ASSEP thresholds in the range 0 to 55 dB HL revealed a significant correlation at each of the test frequencies (500 Hz: r = .645, F = 21.35, df = 1, 30, p < .01; 1000 Hz: r = .518, F = 13.63, df = 1, 37, p < .01; 2000 Hz: r = .737, F = 34.53, df = 1, 29, p < .01; 4000 Hz: r = .616, F = 22.11, df = 1, 36, p < .01). The regression formulae are given in Table 4.

Figure 4 shows the behavioral hearing levels obtained for each carrier frequency on occasions in which the ASSEP was absent at maximum presentation levels (120 dB HL). ASSEP absence was in all cases consistent with profound hearing loss and in 470 of the 517 occasions (90.9%) was consistent with hearing levels ≥ 115 dB HL.

DISCUSSION

The results presented in this article indicate that there are strong relationships between ASSEP thresholds determined in infancy and subsequently obtained behavioral thresholds in babies with normal hearing or with sen-

sorineural hearing loss. In a previous study, using the same equipment and recording techniques, we found that simple linear regression lines could be used to predict behavioral thresholds from ASSEP thresholds in young children (≥ 10 months) and adults with sensorineural hearing loss (Rance et al, 1995). The results of the present study confirm that for babies with elevated ASSEP thresholds (60 dB HL or greater), a similar ASSEP/behavioral threshold relationship applies. Hearing thresholds in these ears were typically found within 5 to 10 dB of the levels predicted by the 1995 regression formulae. As such, the ASSEP findings in these cases provided an accurate basis for intervention, and all of the infants were successfully amplified within 1 month of their ASSEP assessment (mean age = 4 months).

The results for infants with ASSEP thresholds less than 60 dB HL were, however, quite different from those obtained from their older counterparts. Broadly speaking, behavioral threshold in these babies with normal or near-normal hearing was 10 to 15 dB better than

A Frequency (Hz)

B Frequency (Hz)

C Frequency (Hz)
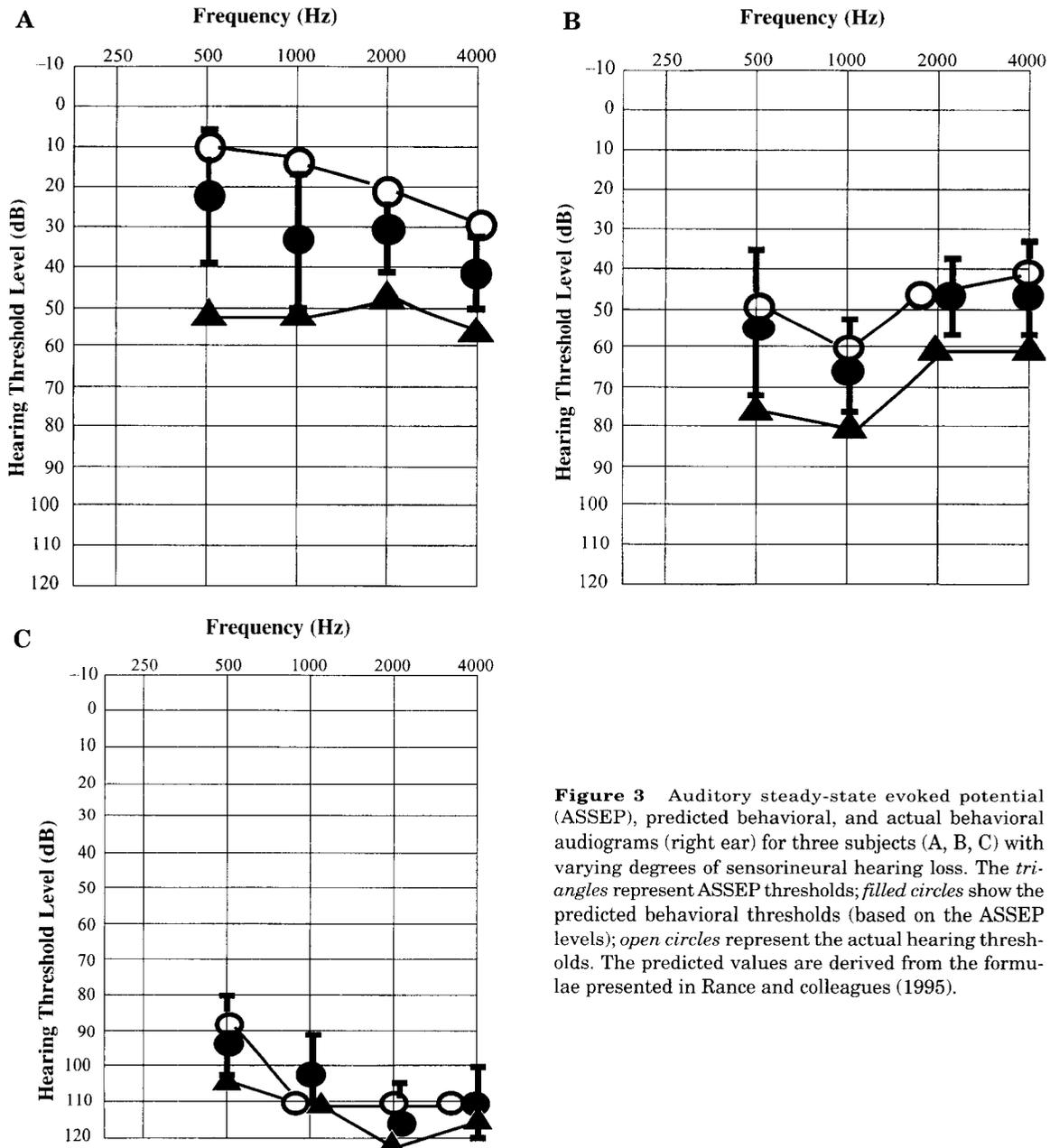
Figure 3 Auditory steady-state evoked potential (ASSEP), predicted behavioral, and actual behavioral audiograms (right ear) for three subjects (A, B, C) with varying degrees of sensorineural hearing loss. The *triangles* represent ASSEP thresholds; *filled circles* show the predicted behavioral thresholds (based on the ASSEP levels); *open circles* represent the actual hearing thresholds. The predicted values are derived from the formulae presented in Rance and colleagues (1995).

predicted by the Rance and colleagues' (1995) data. According to the 1995 formulae, ASSEP thresholds around 20 to 30 dB HL would be expected for subjects with normal hearing. Other studies of normal adults using ASSEPs at modulation rates higher than 70 Hz have shown similar results (Lins and Picton, 1995; Lins et al, 1995, 1996; Aoyagi et al, 1994; Picton et al, 1998; Herdman and Stapells, 2001). In contrast, ASSEP thresholds in our infant subjects with normal hearing and mild hearing loss were typically obtained at sensation levels of approximately 30 to 40 dB.

Table 4 Linear Regression Formulae for the Distribution of ASSEP/Behavioral Hearing Threshold Comparisons for Ears in ASSEP Category 1 (0–55 dB HL)

Frequency (Hz)

500	y = 0.72x − 23.1
1000	y = 0.84x − 27.7
2000	y = 0.95x − 25.4
4000	y = 1.14x − 33.3

y = predicted behavioral threshold; x = auditory steady-state evoked potential (ASSEP) threshold.

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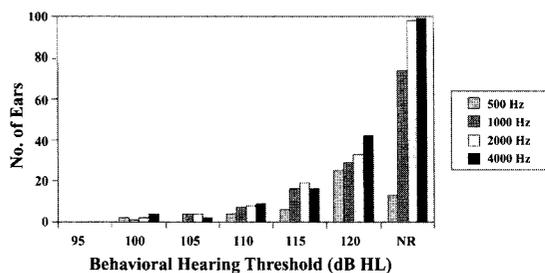
Figure 4 Behavioral hearing thresholds in ears with absent auditory steady-state evoked potentials at maximum presentation levels (120 dB HL).

Other studies have reported ASSEP thresholds at similar levels in normal neonates and babies. Rickards and colleagues (1994), using the same system as that employed in the present study, found mean ASSEP thresholds in normal neonates to be in the range of 25 to 40 dB HL. Lins and colleagues (1996) studied 21 well babies and found mean thresholds in the range of 20 to 35 dB HL. Although these values are closer to adult levels than the Rickards and colleagues' (1994) neonatal findings, Lins and colleagues (1996) did show in a direct comparison with a group of adult subjects a significant difference in mean threshold at 500 Hz, and they also showed a general tendency across frequencies for baby ASSEP thresholds to be higher than for adults.

Taken overall, the evidence suggests a developmental improvement in ASSEP thresholds in babies with normal hearing or mild sensorineural hearing loss in the first few months of life. Several studies have demonstrated similar ABR threshold changes in the early weeks of life. Although the time course for the ABR threshold changes is unclear, numerous studies have found that thresholds in neonates are elevated relative to adult levels, and they have shown that the normal adult range may not be reached until several weeks after birth (Schulman-Galambos and Galambos, 1979; Klein, 1984; Folsom and Wynne, 1986; Adelman et al, 1990; Sininger et al, 1997). As the high-rate (70-Hz) ASSEP is thought to be generated in the auditory brain stem (Kuwada et al, 1986; Cohen et al, 1991), it is possible that the maturational processes that affect the ABR may also exert an influence over the maturing ASSEP.

In conclusion, the data presented in this study suggest that the ASSEP regression formulae from Rance and colleagues (1995) can confidently be applied to babies for threshold estimation provided that the ASSEP levels are 60 dB HL or greater. Different regression formulae may, however, be appropriate when babies are less than 3 to 6 months of age and the ASSEP threshold is < 60 dB HL.

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