Correlations Between Audiogram and Objective Hearing Tests in Sensorineural Hearing Loss

L. Bishara,[1] J. Ben-David,[1] L. Podoshin,[1] M. Fradis,[1] C.B. Teszler,[1] H. Pratt,[2] T. Shpack,[3] H. Feiglin,[3] H. Hafner,[3] and N. Herlinger[2]

[1]Department of Otolaryngology, Head and Neck Surgery, and [3]Institute of Audiology, Bnai-Zion Medical Center, and [2]Evoked Potentials Laboratory, Technion, Haifa, Israel

Abstract: Owing to its subjective nature, behavioral pure-tone audiometry often is an unreliable testing method in uncooperative subjects, and assessing the true hearing threshold becomes difficult. In such cases, objective tests are used for hearing-threshold determination (i.e., auditory brainstem evoked potentials [ABEP] and frequency-specific auditory evoked potentials: slow negative response at 10 msec [SN-10]).

The purpose of this study was to evaluate the correlation between pure-tone audiogram shape and the predictive accuracy of SN-10 and ABEP in normal controls and in patients suffering from sensorineural hearing loss (SNHL).

One-hundred-and-fifty subjects aged 15 to 70, some with normal hearing and the remainder with SNHL, were tested prospectively in a double-blind design. The battery of tests included pure-tone audiometry (air and bone conduction), speech reception threshold, ABEP, and SN-10. Patients with SNHL were divided into four categories according to audiogram shape (i.e., flat, ascending, descending, and all other shapes).

The results showed that ABEP predicts behavioral thresholds at 3 kHz and 4 kHz in cases of high-frequency hearing loss. Also demonstrated was that ABEP threshold estimation at 3 kHz was not affected significantly by audiogram contour. A good correlation was observed between SN-10 and psychoacoustic thresholds at 1 kHz, the only exception being the group of subjects with ascending audiogram, in which SN-10 overestimated the hearing threshold.

Keywords: ascending audiogram; audiogram; audiogram shape; auditory brainstem evoked potentials; average audiogram; behavioral audiometry; behavioral threshold; electrophysiological threshold; frequency-specific auditory evoked potentials; objective hearing tests; predictive accuracy; psychoacoustic threshold; sensorineural hearing loss

Owing to its subjective nature, behavioral pure-tone audiometry often is an unreliable testing method in uncooperative subjects (e.g., children, malingerers), and assessing the true hearing threshold becomes difficult. In such cases, objective tests are used for hearing-threshold determination (i.e., auditory brainstem evoked potentials [ABEP], and frequency-specific auditory evoked potentials (SN-10).

Reprint requests: J. Ben-David, M.D., Department of Otolaryngology, Head and Neck Surgery, Bnai-Zion Medical Center, 47 Golomb Street, P.O. Box 4940, Haifa 31048, Israel. E-mail: teszler@hotmail.com

This work was presented at The Twenty-Fifth Ordinary Congress of the Neurootological and Equilibriometric Society, Bad Kissingen, Germany, 1998.

ABEPs have been recorded clearly in children and adults [1], regardless of state of consciousness [2], degree of concentration (listening) [3], and sedation. Measurements of ABEP are not measures of hearing per se but involve sound-elicited potentials arising in the auditory nerve and brainstem structures (by which ABEP was established as an important procedure for testing brainstem activity in various pathologies [4–9]). In contrast, behavioral audiometry is based on hearing in terms of the perceptual process involving the entire auditory system. Nevertheless, the hearing thresholds determined by the two methods in cooperative subjects lie in fairly close proximity of each other [10,11].

ABEP is not completely objective inasmuch as the interpretation of results depends on the examiner's judgment with respect to the existence of neuronal activity in the background noise [12]. Interpretation may prove difficult when the signal-to-noise ratio is very low. Even when the latter is enhanced, contrasting repeat recordings is not clear-cut, especially when the signal-to-noise ratios are not identical. The noise problem can occur even after very many repetitions [13], in which case it is up to the operator to perform time-consuming additional repetitions to obtain a sufficient overlap between recordings [12].

Another disadvantage of ABEP comes with the need for high synchronization. Consequently, clicks with the main frequency at 3 to 4 kHz are used instead of the lower frequencies of speech (0.5–2 kHz). Davis and Hirsch [14] and Suzuki and Horiuchi [15] have described another response at approximately 10 msec after stimulus onset. They labeled this the *slow negative response at 10 msec* (SN-10), and its generator is believed to be the dendritic activity in the gray matter, especially the inferior colliculus. This wave is obtained 20 dB above audiometric thresholds; because less synchronization is required to elicit it as compared to ABEP, usually it is evoked best with tone bursts at 1,000 Hz [16]. Hence, the method of choice for threshold determination in the speech frequency range (especially 1,000 Hz) is SN-10 [17]. The technique also exhibits some inconveniences. It runs the risk of being masked by the frequency-following response when intense stimuli are used, especially at lower frequencies (e.g., 500 Hz) [18]. Additionally, the same signal-noise problem must be addressed as in ABEP recordings.

Few studies focused on the ability of an audiogram profile to predict hearing threshold. A good correlation was found between the threshold of evoked potentials and audiometric thresholds in patients with gently sloping audiograms [19,20]. Most studies found a high correlation between psychoacoustic thresholds in the lower frequencies and those determined by SN-10, with the specification that some discrepancy is possible [19–21]. The influence of audiogram contour on threshold evaluation by SN-10 has not been reported.

We undertook this study to evaluate the correlation between pure-tone audiogram shape and the predictive accuracy of SN-10 and ABEP in normal and hearing-impaired subjects. Furthermore, comparing the precision of these tests seemed a compelling objective, as all have been known to bear some inaccuracies (as mentioned).

MATERIALS AND METHODS

We prospectively studied 150 normal subjects and patients with sensorineural hearing loss (SNHL; Table 1). Uncooperative patients and those suspected of pursuing a secondary gain and thereby biasing their reliability (some victims of traffic and work accidents) were excluded from the study. Criteria for the control group included normal hearing at 250–8,000 Hz, negative otoscopy, absent history of noise exposure, and a good general health.

Table 1. Classification of Study Participants

Subjects	Number	Age Range (yr)	Mean Age (yr)
Normal controls	19	17–62	34
SNHL	131	15–75	51

SNHL = sensorineural hearing loss.

All participants underwent pure-tone audiometry (air and bone conduction; range, 250–8,000 Hz); speech reception threshold testing; ABEP assessment (20 clicks/sec with alternating polarity, ×200,000 signal amplification and 10- to 3,000-Hz filtering); and SN-10 recording (1,000-Hz pure-tone, with a 2-1-2 stimulation pattern at 20-sec repetition rate, ×200,000 signal amplification and 30- to 30,000-Hz filtering).

To minimize interference caused by subjects' muscle tone, 10 mg diazepam (Valium) PO was administered during ABEP and SN-10 recordings. A double-blind design was devised with the purpose of improving accuracy of findings and of preventing mutual influences between audiometry and objective hearing tests. In that way, audiometry was carried out by one examiner, whereas a second independent operator performed SN-10 and ABEP recordings.

RESULTS

Keeping in mind that we intended to study the correlation between audiogram profile and objective hearing threshold, the patients with SNHL first were divided into four categories according to audiogram shape (i.e., flat, ascending, descending, and other); a fifth group consisted of healthy subjects with normal hearing (Table 2). We termed as *ascending* and *descending* those audiograms in which the threshold difference between two adjacent frequencies, one octave apart, was more than 20 dB. *Other* includes all the audiograms that could not be included in any other group. Subsequently, the mean thresholds were calculated for every pure-tone frequency. This step re-

Table 2. Demographics by Audiogram Shape

Audiogram Type	No. of Ears	Mean Age (yr)
Normal	38	34
Flat	49	52
Ascending	14	50
Descending	119	56
Other	42	45

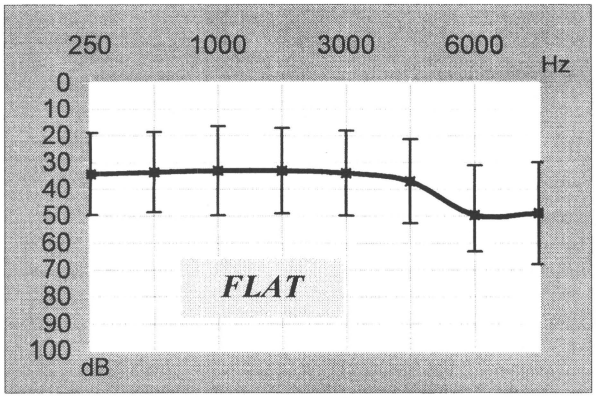

Figure 1. Average audiogram of the flat type in sensorineural hearing loss.

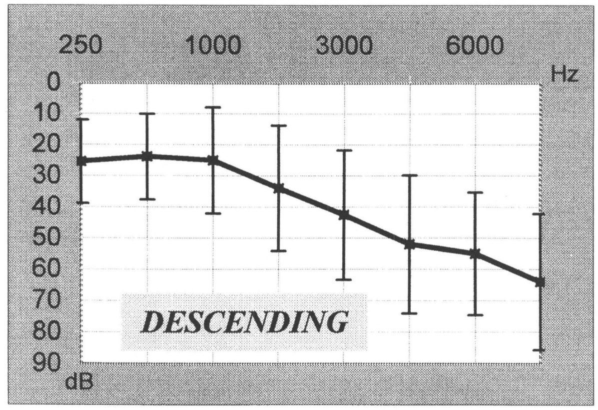

Figure 3. Average audiogram of the descending type in patients with sensorineural hearing loss.

sulted in an "average audiogram" for each of the four categories of audiogram contour (Figs. 1–4).

With a view to predicting audiometric thresholds on the basis of objective hearing tests, we next verified the extent of their relative proximity by calculating the arithmetical difference (in decibels) between them. Two parameters were determined in each audiometric category: frequency-matched threshold differences between ABEP and behavioral audiometry (Fig. 5), the lowest difference being found at 3 kHz in all four pathological categories, and threshold differences between SN-10 (at 1 kHz) and audiometric thresholds by profile categories (Fig. 6). The threshold difference was calculated for the 0.5-kHz, 1-kHz, and 2-kHz frequencies and for the average threshold at these three frequencies. Additionally, the speech reception threshold was included. The smallest difference was observed at the 1-kHz frequency and the speech reception threshold, but it increased in the group with ascending-type audiogram (i.e., SN-10 best approximated the 1-kHz-threshold). However, its accuracy significantly decreased in patients with audiograms of ascending contour (analysis of variance).

To improve our ability to predict an accurate threshold by means of the ABEP threshold, a linear regression analysis evaluated the correlation between the ABEP and audiometry thresholds at seven pure-tone frequencies (Table 3). Our findings indicate the best correlation to be at 3 kHz and 4 kHz, with the former showing the highest correlation coefficient (r^2 value = 0.68). Figure 7 depicts the scatter plot of ABEP (electrophysiological) thresholds and the 3-kHz pure-tone thresholds (behavioral). Also shown is the most probable equation relating electrical threshold (ET) to behavioral threshold (BT), as given by linear regression analysis:

$$BT = a \times ET + B$$

where a = slope and B = intercept. By use of such an equation, the behavioral threshold can be predicted at the other pure-tone frequencies. The simple extrapola-

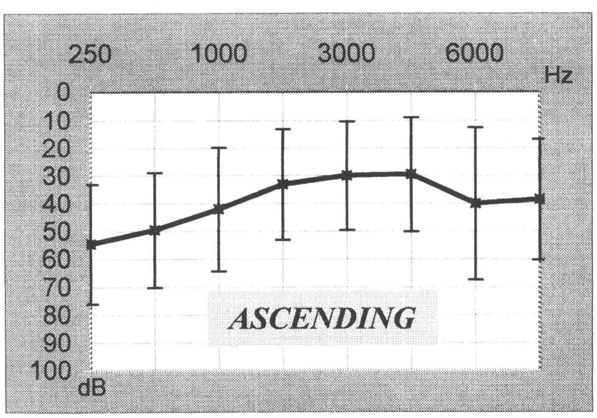

Figure 2. Average audiogram of the ascending type in the studied patients with sensorineural hearing loss.

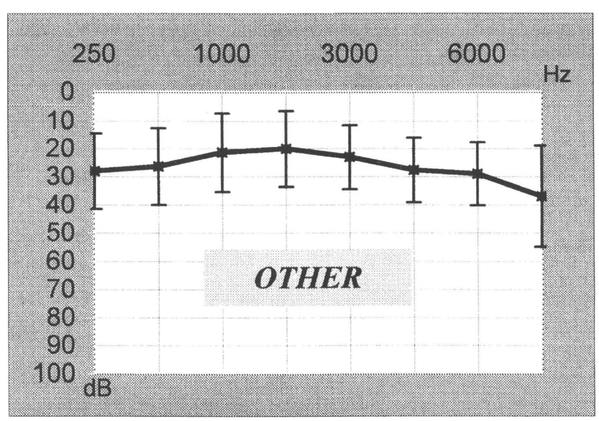

Figure 4. Average audiogram of sensorineural hearing loss patients not fitting any of the shapes described in Figures 1–3.

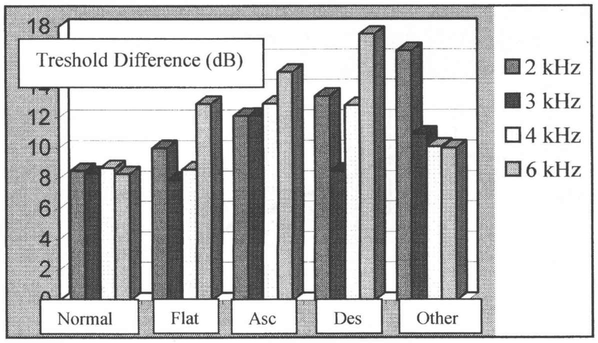

Figure 5. Threshold differences between auditory brainstem evoked potentials and behavioral audiometry as a function of audiogram shape. (*Asc* = ascending; *Des* = descending.)

Table 3. Auditory Brainstem Evoked Potentials: Audiometry Correlation at Various Frequencies as Given by Linear Regression Analysis

Frequency (Hz)	Regression BT = a × ET + b	r^2
250	0.4 × ET + 11.4	0.22
500	0.45 × ET + 8.5	0.26
1,000	0.58 × ET + 2.85	0.37
2,000	0.78 × ET − 0.72	0.53
3,000*	0.94 × ET − 2.9	**0.68**
4,000	0.99 × ET + 0.18	0.6
6,000	1.01 × ET + 4.63	0.47

a = slope; B = intercept; r^2 = correlation coefficient; BT = behavioral threshold; ET = electrical threshold.
*The best correlation was found at 3 KHz.

tion of the known ET yields the probable BT. However, as the best correlation is at 3 and 4 kHz, it must be kept in mind that the error range is likely to increase at the other frequencies.

The same regression analysis was conducted in the case of SN-10 versus psychoacoustic thresholds. The best correlation was found at the 1-kHz frequency (Table 4). Figure 8 reproduces this linear correlation. The SN-10: audiometry correlation varied greatly with audiogram contour: Those in the group with ascending audiograms departed from all the other categories (i.e., flat, descending, and other). This outcome may result from better hearing at higher frequencies, biasing the threshold estimate for 1 kHz. In contrast, ABEP estimating the 3-kHz threshold was not affected by audiogram profile.

DISCUSSION

This study evaluated the predictive accuracy of objective hearing test results (ABEP, SN-10) by comparison to behavioral results obtained by conventional pure-tone audiometry. A good correlation between electrophysiological and behavioral thresholds in subjects with mildly sloping audiograms is reflected in the works of Hayes and Jerger [19] and of Stappells and Picton [20]. In the findings of the former, 98% and 91% of evoked responses were within a range of 30 and 20 dB above the behavioral threshold, respectively. The second study analyzed the flat and mildly slanting audiograms of 37 children with mild to severe hearing loss and found that the ET accurately predicted the psychoacoustic threshold. This correlation decreased in the steeper audiograms, mostly in the 500- to 1,000-Hz range.

Davis et al. [22] found that ABEP audiograms for "flat" hearing losses did not differ significantly from their corresponding pure-tone audiograms. However, the slopes for steep high-frequency hearing losses were underestimated. In our study, ABEP predicted behavioral thresholds at 3 kHz and 4 kHz in cases of high-frequency hearing loss. In light of this finding, it con-

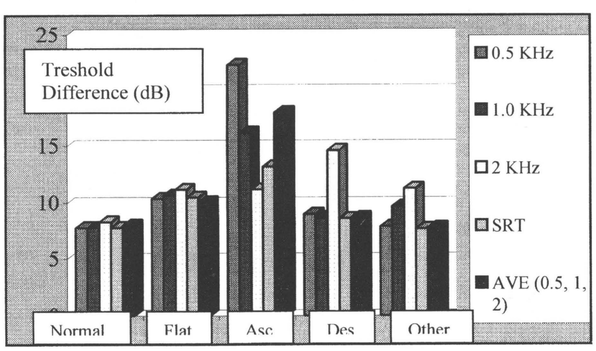

Figure 6. Threshold difference between slow negative response at 10 msec and pure-tone audiometry as a function of audiogram contour. (*Asc* = ascending; *Des* = descending; *AVE* = average of three frequencies: 0.5, 1, and 2 kHz.)

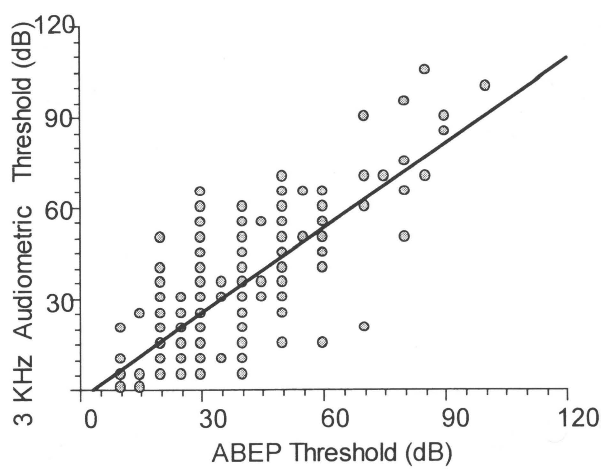

Figure 7. Auditory brainstem evoked potentials (*ABEP*) threshold versus the 3-kHz audiometric threshold.

Table 4. Slow Negative Response at 10 msec Audiometry Correlation at Various Frequencies as Given by Linear Regression Analysis

Frequency (Hz)	Regression BT = a × ET + b	r^2
250	0.74 × ET + 7.8	0.32
500	0.82 × ET + 4.4	0.38
1,000*	0.97 × ET − 0.43	**0.45**
2,000	0.98 × ET + 2.3	0.53
3,000	0.95 × ET + 6.9	0.68
4,000	0.89 × ET + 13.7	0.6
6,000	1.01 × ET + 14.1	0.47

a = slope; B = intercept; r^2 = correlation coefficient; BT = behavioral threshold; RT = reception threshold; ET = electrical threshold.
*The best correlation was found at 1 kHz.

firmed the results of Stappells and Picton [20], as the results had been obtained similarly from SNHL patients with mildly sloping audiograms. ABEP threshold estimation at 3 kHz was not affected significantly by audiogram contour in our population.

Fowler and Swanson [21] investigated the accuracy of threshold estimates by SN-10 in subjects with low-frequency SNHL [21]. Seventy percent of the obtained thresholds lay within a range of 20 dB above psychoacoustic threshold at the studied frequencies (500, 1,500, 3,000 Hz). Similarly, our results showed a good correlation between SN-10 and psychoacoustic thresholds at 1 kHz. The only exception was the group of subjects with ascending audiogram; in them, SN-10 overestimated the hearing threshold. A possible explanation for this phenomenon would be the contribution of the higher frequencies (i.e., those with better thresholds in the ascending audiogram). Therefore, whenever an ascending audiogram is suspected in typical cases in

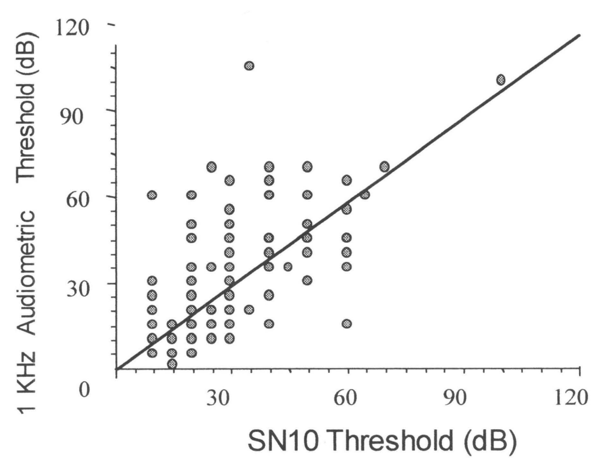

Figure 8. Slow negative response at the 10-msec (*SN10*) threshold versus the 1-kHz audiometric threshold.

which SN-10 is needed, high-frequency masking may improve accuracy.

CONCLUSIONS

ABEP predicted behavioral thresholds at 3 kHz and 4 kHz in cases of high-frequency hearing loss. ABEP threshold estimation at 3 kHz was not affected significantly by audiogram contour. A good correlation between SN-10 and psychoacoustic thresholds at 1 kHz was found; the only exception was the group of subjects with an ascending audiogram; in them, SN-10 overestimated the hearing threshold.

REFERENCES

1. Hecox K, Galambos R. Brainstem auditory evoked response in human infants and adults. *Arch Otolaryngol* 99:30–33, 1974.
2. Allen DM, Starr A. Effect of click rate on the latency of the auditory brainstem response in humans. *Ann Otol Rhinol Laryngol* 86:186–195, 1977.
3. Picton TW, Hillyard SA. Human auditory evoked potentials: II. Effects of attention. *Electroencephalogr Clin Neurophysiol* 36:191–199, 1974.
4. Ben-David J, Gertner R, Podoshin L, et al. Auditory brain stem evoked potentials in patients suffering from peripheral facial nerve palsy and diabetes mellitus. *J Laryngol Otol* 100:629–933, 1986.
5. Ben-David J, Pratt H, Landman L, et al. A comparison of auditory brain stem evoked potentials in hyperlipidemics and normolipemic subjects. *Laryngoscope* 92:186–189, 1986.
6. Podoshin L, Fradis M, Ben-David J, et al. Auditory brain stem evoked potentials in patients with migraine. *Headache* 27:27–29, 1987.
7. Podoshin L, Ben-David J, Fradis M, et al. Brainstem auditory evoked potentials with increased stimulus rate in minor head trauma. *J Laryngol Otol* 104:191–194, 1990.
8. Pratt H, Ben-David J, Peled R, et al. Auditory brain stem evoked potentials: clinical promise of increased clinical rate. *Electroencephalogr Clin Neurophysiol* 51:80–90, 1981.
9. Pratt H, Brodsky G, Goldsher M, et al. Auditory brain stem evoked potentials in patients undergoing dialysis. *Electroencephalogr Clin Neurophysiol* 63:18–24, 1986.
10. Elberling C, Don M. Detection functions for the human auditory brainstem response. *Scand Audiol* 16:89–92, 1987.
11. Sininger YS, Don M. Effect of click rate and electrode orientation on threshold detectability of the auditory brainstem response. *J Speech Hear Res* 32:880–886, 1989.
12. Sininger YS. Auditory brainstem response for objective measures of hearing. *Ear Hear* 14(1):23–30, 1993.
13. Sininger YS, Msuda A. Effects of click rate and electrode orientation on threshold detectability of the auditory brainstem response. *J Speech Hear Res* 32:880–886, 1989.

14. Davis H, Hirsh S. A slow brainstem response for low-frequency audiometry. *Audiology* 18:445–461, 1979.

15. Suzuki T, Horiuchi K. Effects of high-pass filter on auditory brainstem responses to tone pips. *Scand Audiol* 6:123–125, 1977.

16. Hawes M, Greenberg H. Slow brainstem responses (SN10) to tone pips in normally hearing newborns and adults. *Audiology* 20:113–122, 1981.

17. Tawfik S, Musiek FE. SN10 Auditory brainstem evoked potential revised. *Am J Otol* 12(3):179–183, 1991.

18. Davis H. Principles of electric response audiometry. *Ann Otol Rhinol Laryngol* 3(28):S1–S96, 1976.

19. Hayes D, Jerger J. Auditory brainstem response (ABR) to tone pips, results in normal and hearing impaired subjects. *Scand Audiol* 11:113–122, 1982.

20. Stapells DR, Picton TW. Threshold of short latency auditory evoked potentials to tone in notched noise in normal hearing and hearing impaired subjects. *Audiology* 29: 262–274, 1990

21. Fowler CG, Swanson MR. The 40-H potential and SN10 as a measure of low frequency thresholds. *Scand Audiol* 18(1):27–33, 1989.

22. Davis H, Hirsch SK, Popelka GR, Fomb C. Frequency selectivity and threshold by brief stimuli suitable for electric response audiometry. *Audiology* 23:59–74, 1984.