Thresholds for Auditory Brain Stem Responses to Tones in Notched Noise from Infants and Young Children with Normal Hearing or Sensorineural Hearing Loss

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Objective: **To assess the accuracy of threshold estimates determined using the auditory brain stem responses (ABRs) to brief tones presented in notched noise in a group of infants and young children with normal hearing or sensorineural hearing loss (SNHL).**

Design: **The thresholds for ABRs to brief duration 500, 2000, and 4000 Hz tones presented in notched-noise masking were evaluated in infants and young children with normal hearing (*N* = 34) or SNHL (*N* = 54). Tone-evoked ABR thresholds were compared with behavioral thresholds obtained at follow-up audiologic assessments, for a total of 220 comparisons.**

Results: **ABR thresholds for the infants with bilateral normal hearing were 23.6, 12.9, and 12.6 dB nHL for 500, 2000 and 4000 Hz, respectively. Most (92 to 100%) infants with normal hearing showed ABRs to 30 dB nHL tones. Across all subjects (i.e., those with normal hearing and those with impaired hearing), high (≥0.94) correlations were found between the ABR and behavioral thresholds. The mean differences between ABR (dB nHL) and behavioral (dB HL) thresholds across all subjects were 8.6, −0.4, and −4.3 dB for 500, 2000, and 4000 Hz, respectively. Overall, 98% of the ABR thresholds were within 30 dB of the behavioral thresholds, 93% were within 20 dB, and 80% were within 15 dB.**

Conclusions: **These threshold results for the ABR to brief tones in notched noise obtained for infants and young children are similar to those obtained in similar studies of adults. The technique may be used clinically with reasonable accuracy to estimate pure-tone behavioral thresholds in infants and young children who are referred for diagnostic threshold ABR testing.**

(Ear & Hearing 1995;16;361–371)

The click-evoked auditory brain stem response (ABR) is the most widely employed procedure for the electrophysiological evaluation of auditory threshold in infants and young children when their behavioral audiometric results are unobtainable or unreliable. The ABR to clicks alone, however, cannot provide information concerning sensitivity for specific frequencies. Furthermore, hearing loss restricted to particular frequency regions may be underestimated or missed entirely by the click-ABR threshold (e.g., Picton, 1978; Picton & Durieux-Smith, 1988; Picton, Ouellette, Hamel, & Durieux-Smith, 1979; Stapells, 1989; Yamada, Yagi, Yamane & Suzuki, 1975). An alternative and more frequency-specific approach to obtain electrophysiologic thresholds is to record the ABRs to brief-duration tonal stimuli.

Numerous studies have investigated the ABRs to tonal stimuli (for a review, see Stapells, Picton, & Durieux-Smith, 1994). In terms of estimating behavioral thresholds in hearing-impaired subjects, most studies have indicated reasonably accurate and reliable results for frequencies from 500 to at least 4000 Hz (e.g., Hayes & Jerger, 1982; Kileny & Magathan, 1987; Kodera, Yamane, Yamada & Suzuki, 1977; McGee & Clemis, 1980; Munnerley, Greville, Purdy, & Keith, 1991; Picton et al, 1979; Stapells, Picton, Durieux-Smith, Edwards, & Moran, 1990; Suzuki, Kodera & Yamada, 1984; Suzuki & Yamane, 1982), although a small number have indicated inaccuracies and difficulties occurring for 500 Hz (Davis & Hirsh, 1976; Gorga, Kaminski, Beauchaine & Jesteadt, 1988; Hayes & Jerger, 1982; Laukli, 1983; Laukli, Fjermedal & Mair, 1988; Sohmer & Kinarti, 1984). Some of these difficulties may be attributed to various problems, including high-pass EEG filter set too high, use of EEG recording channel contralateral to the ear-stimulated, high levels of ipsilateral masking noise, high levels of acoustic ambient noise and/or electrically noisy environment (e.g., operating room), stimuli which were either too brief or too long, too few trials per average, and/or waveform interpretation issues.

Several studies have investigated the tone-evoked ABRs in infants and young children (Hyde, 1985; Stapells, 1989; Stapells et al, 1994; Stockard, Stockard & Coen, 1983; Suzuki et al, 1984;), and most indicate the responses are detectable at inten-

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sities similar to those in adult subjects. Our recent studies have indicated normal "screening" intensities for infants aged 2 weeks or older are 30–40 dB nHL at 500 Hz, and 20–30 dB nHL at 2000 and 4000 Hz (Stapells, 1989; Stapells et al, 1994). Studies of the tone ABR in infants and young children with hearing impairments are few but have indicated reasonable estimates of their behavioral audiograms (e.g., Kileny & Magathan, 1987; Suzuki et al, 1984). Generally, these studies have been in relatively small groups of children with hearing impairments or in children from whom behavioral audiometric information has been questionable.

The brief tones required to elicit synchronous ABRs contain significant acoustic splatter in frequencies above and below the tones' nominal frequencies. Studies in subjects with normal hearing have indicated that responses to brief tones presented at intensities greater than 40–50 dB nHL, or about 70 dB peak-to-peak equivalent SPL, contain contributions from this acoustic splatter and hence have reduced frequency specificity (for a review, see Stapells et al, 1994). This is true whether the tones be 500, 1000, 2000, or 4000 Hz. Furthermore, regardless of how "pure" a tonal stimulus may be (e.g., a tone of several seconds duration and thus containing essentially no acoustic splatter), above about 70 dB SPL upward spread of excitation occurring as a result of cochlear physiology rather than acoustic splatter will result in contributions arising from frequencies above the tones' nominal frequencies (Pickles, 1986). These issues have led to the suggestion of the use of simultaneous ipsilateral noise masking to improve the frequency specificity of the ABRs to these brief tones (Picton, 1978; Picton et al, 1979).

High-pass filtered noise may be employed to mask upward spread of excitation as well as the acoustic splatter to frequencies above the tone frequency (e.g., Kileny & Magathan, 1987); however, it does not mask splatter to frequencies lower than the tone frequency. This is particularly significant in the case of steeply sloping high frequency impairments where sensitivity at a lower frequency is much better than that at a higher frequency (Picton, 1978; Picton et al, 1979; Purdy & Abbas, 1989; Stapells, 1984; Stapells et al, 1990; Stapells et al, 1994). Mixing "notched" (band reject) masking noise with the brief tones has been suggested as a solution (Picton et al, 1979). The effects of the notched-noise masking on the ABRs to brief tones have been reviewed (Stapells et al, 1990, 1994). Results of two different centers' recent studies of adults with normal hearing (Purdy et al, 1989; Stapells et al, 1990) and impaired hearing (Stapells et al, 1990; Munnerley et al, 1991) have indicated reasonably accurate ABR estimates of pure tone behavioral threshold using the technique of recording the ABR to brief tones in notched noise. No studies of this technique in groups of infants or young children with hearing impairments have been published.

The purpose of the present study was to assess the accuracy of threshold estimates determined using the ABR to brief tones presented in notched noise in a group of infants and young children with sensorineural hearing loss referred for clinical testing, as well as in a group of infants and young children with normal hearing. The ABR thresholds were compared with pure tone behavioral audiometric thresholds obtained at follow-up, usually at a later age.

METHODS

A total of 88 infants and young children, aged 1 week to 8 yr (mean age at ABR = 31 mo; median age = 21 mo; 77% of subjects aged less than 48 mo) participated in this study. Thirty-four subjects had normal hearing, whereas 54 subjects had sensorineural hearing loss (SNHL). Six of the subjects had unilateral sensorineural impairments with normal hearing in the other ear. Subjects with bilateral normal hearing were recruited as part of their participation in a multivisit longitudinal research program.

Subjects with hearing loss were specifically referred for clinical ABR testing by our Auditory Behavioral Laboratory, by other clinical facilities associated with the Albert Einstein College of Medicine/Montefiore Medical Center (AECOM/MMC), as well as by outside agencies. Owing to the clinical nature of this study, the specific audiometric test equipment used to obtain behavioral audiograms and acoustic immittance measures varied by facility. All ABR testing (and same-day acoustic immittance measures) was completed in the AECOM Auditory Evoked Potential Laboratories.

Behavioral audiograms were obtained independently of the ABR assessment: approximately 90% of the behavioral tests were completed by our related AECOM/MMC laboratories and clinics (all of the normal-hearing group and the majority of the subjects in the SNHL group); 10% were obtained by other clinical facilities (SNHL group). The average age for behavioral audiometric testing was 33.9 ± 25.4 mo (median age = 28.1 mo). On average, these audiograms were obtained within 2.2 ± 18.0 mo of the ABR testing, with some audiograms for the older children being obtained before the ABR.

All audiograms considered in this investigation were deemed reliable by the audiologist completing the behavioral audiogram. This was based on the subjective judgment of the audiologist or an actual quantification of false-positive responding (percentage of responses to control trial intervals). If the reliability of the behavioral audiogram was questionable, the result was not considered. If more than one audiogram was available for a child, the one deemed most reliable was used in the analyses.

Only audiometric threshold data were considered. Behavioral test results that were obtained using behavioral observation audiometry or that were considered "minimal response levels" rather than threshold values were excluded from this study. Consequently, audiograms obtained using only visual reinforcement audiometry, play audiometry, or in a few cases, conventional audiometric test procedures, were included in the analyses. Air conduction thresholds were obtained using conventional supra-aural earphones (i.e., TDH-39, TDH-49, etc., with MX41/AR cushions). No thresholds obtained in sound field were considered. If masking was not used in cases of threshold asymmetry, the audiogram was excluded from the study.

Inclusion in this study required evidence of no conductive component at the time of the ABR and behavioral tests. This was determined by either the absence of an air-bone gap (when bone conduction thresholds were available) and/or by normal acoustic immittance results. Following the qualitative classification scheme suggested by Jerger (1970), a tympanogram with normal compliance and peak pressure between +50 and −150 daPa was considered as evidence of the absence of significant middle ear pathology. The presence of the acoustic reflex (when available and with consideration of the degree of the loss) provided further evidence of normal middle ear function. In the few cases with tympanometric pressure peaks less than −150 daPa (type C), present acoustic reflexes were required in order for the data to be included. In no case were threshold data included when a noncompliant (flat, type B) tympanogram was recorded on the day of testing. A 220 Hz probe frequency was used in the majority of cases.

Inclusion in the group with normal hearing required behavioral thresholds at or better than 25 dB HL for 500 to 4000 Hz. Inclusion in the group with sensorineural hearing loss required behavioral thresholds for one or more of 500, 2000, and 4000 Hz to be greater than 25 dB HL. Mean (and standard deviation) pure-tone behavioral thresholds are given for each group in Table 1.

TABLE 1. Pure-tone behavioral thresholds (dB HL) for normal-hearing and sensorineural-impaired (SNHL) ears

	Frequency (Hz)		
	500	2000	4000
Normal-hearing ears:			
Mean	15.9	13.2	13.8
SD	7.9	6.8	6.1
N[a]	39	39	41
SNHL ears:			
Mean	64.6	74.2	79.2
SD	33.8	34.1	33.1
N[b]	77	78	70

[a] *N, number of ears with normal thresholds contributing data to study. Includes results for six normal ears from subjects with unilateral SNHL.*

[b] *N, number of ears with SNHL contributing data to the study.*

Stimuli for ABR testing were 500, 2000, and 4000 Hz short duration tones presented in notched noise. The tones had linear rise times equaling two cycles, plateau times of one cycle, and linear fall times of two cycles. The normal behavioral thresholds (0 dB nHL) for these stimuli are 24.6, 26.1, and 29 dB peak-to-peak equivalent (pe) SPL for the 500, 2000, and 4000 Hz tones, respectively (Stapells et al, 1990). The tones were presented monaurally at a rate of 39.1/sec using a Telephonics TDH-49 earphone (MX41/AR cushion). This rate was the fastest rate allowed by our equipment when using a 25-msec analysis time. The notched noise was produced by passing broadband noise through a band-reject filter (one octave-wide notch centered on the nominal frequency of the tone) with high-pass and low-pass rejection slopes of 48 dB per octave. The noise intensity (in dB SPL) before filtering was set 20 dB below the pe SPL of the tone. This tone-to-noise ratio was maintained for all tone intensities. These stimuli and noise maskers are the same as those used in an earlier study carried out in adults (Stapells et al, 1990). The ear contralateral to that being assessed was masked using white noise set 30 dB below the level required to mask ipsilaterally (Stapells, 1984). Stimuli and noise maskers were calibrated using a Brüel and Kjaer 2209 sound level meter and NBS 9-A earphone coupler (Brüel & Kjaer type 4152 with a 1-inch microphone type 4144).

Single-channel recordings of the brain stem responses were obtained using gold-plated cup electrodes placed at the vertex (noninverting) and mastoid (inverting) ipsilateral to the stimulated ear. A similar electrode placed on the forehead served as a ground. Interelectrode impedances were less than 3000 Ohms. The EEG filter was set to a band pass of 30 to 3000 Hz (12 dB/octave slope) and averaged using a poststimulus analysis time of 25 msec. Trials containing amplitudes exceeding ±25 μV were automatically rejected. At least two replications of 2000 trials each were obtained in each intensity/frequency condition.

All subjects were tested while asleep for ABR testing. Most slept in a crib, but some were seated in a reclining chair or in their parent's arms. Subjects in the group with normal hearing were tested in natural sleep. Subjects in the group with sensorineural hearing loss aged 6 mo or more were sedated by their physician (using chloral hydrate) as part of their clinical assessment; subjects in this group aged under 6 mo were tested in natural sleep. All testing was carried out in a double-walled, sound-attenuating room. Subjects were continuously monitored by intercom, direct visual observation, and by monitoring of their EEG on an oscilloscope. Testing proceeded only when this monitoring indicated the child was asleep and was interrupted during periods of waking or questionable sleep.

Tympanograms (age ≥5 mo: 220 Hz probe frequency; age ≤4 mo: 660 Hz probe frequency; Marchant, McMillan, Shurin, Johnson, Turczyk, Feinstein & Panek, 1986) were obtained during the same sleep session as the ABR test. Ipsilateral acoustic reflexes were also attempted. ABR testing was usually carried out after the acoustic immittance testing.

ABR stimulus/intensity/ear test order was different between the groups with bilateral normal hearing and SNHL. In the group with normal hearing, an ear was randomly chosen, and testing concentrated on that ear. One of the stimulus frequencies was randomly chosen, and threshold was obtained using 10–20 dB steps down to as low as 0 dB nHL. Thresholds for the remaining stimulus frequencies were then obtained for the same ear in random order. When sleep time permitted, thresholds for the other ear were obtained but are not included in this study. This protocol was part of these subjects' participation in a longitudinal study of children with and without otitis media.

ABR testing for the group with SNHL was dictated by clinical concerns. Typically, ABR testing began using 2000 Hz 30 dB nHL tones. If a response was present at 30 dB nHL, then the intensity was dropped to 20 dB nHL and recordings obtained. Recordings at lower intensities were not obtained. If a response was not observed in the 30 dB recording, testing was switched to the other ear, and a similar procedure was carried out. If no response was present to the 30 dB nHL 2000 Hz tones, then a decision regarding what to test next was made based upon the acoustic immittance findings: if immittance findings indicated normal middle ear function then we proceeded to obtain the ABR threshold for the 2000 Hz tones. If the immittance results had not, to this point, been obtained they were then obtained. Ears with abnormal or noninterpretable immittance results were excluded from this study and generally would have received bone conduction ABR testing (Foxe & Stapells, 1993; Stapells & Ruben, 1989). After obtaining thresholds for 2000 Hz in each ear, recordings were then obtained to high-intensity clicks in order to assess VIIIth nerve and brain stem auditory pathway integrity bilaterally (Stapells, 1989). Subjects with abnormal wave V/wave I amplitude ratios (i.e., less than 0.6) were excluded from this study. Thresholds for 500 Hz tones were next obtained bilaterally, with 30 dB nHL being the lowest intensity tested. Finally, sleep time permitting, thresholds for 4000 Hz tones were obtained bilaterally, with 20 dB nHL being the lowest intensity tested. The minima of 20 dB nHL for 2000 and 4000 Hz and 30 dB nHL for 500 Hz were chosen based on normative results (Stapells, 1989; Stapells et al, 1990, 1994) and on clinical efficiency. The number of ABR/behavioral threshold combinations are shown in Table 2, broken down by normal hearing or SNHL, stimulus frequency, and by three age ranges (0 to 6 mo, 7 to 48 mo, ≥49 mo). These age ranges and their numbers are typical of the patient population seen for diagnostic threshold ABR evaluations.

TABLE 2. Number of ABR/behavioral threshold combinations[a] by subject group, stimulus frequency, and age

	Frequency (Hz)		
	500	2000	4000
Normal-hearing ears (40 subjects[b]):			
All ages total	25	28	23
0–6 mo	3	6	3
7–48 mo	22	18	20
≥49 mo	0	4	0
SNHL ears (54 subjects):			
All ages total	48	68	28
0–6 mo	2	5	5
7–48 mo	35	42	15
≥49 mo	11	21	8

[a] *Number of ears contributing data.*
[b] *Includes six subjects with unilateral SNHL.*

Response presence required the agreement of two judges familiar with tone-evoked ABRs. The presence of an ABR in each condition was based primarily upon the replicability of the ABR V-V′ slow wave (Stapells & Picton, 1981; Takagi, Suzuki, & Kobayashi, 1985). Changes in latency and amplitude with stimulus intensity and frequency were also available and helpful to the judges. To rule out contamination by stimulus artifact, only the portion of tracings following the offset of the tonal stimuli (500 Hz: 10 to 25 msec; 2000 Hz: 2.5 to 25 msec; 4000 Hz: 1.25 to 25 msec) were considered by the judges. The judges were not aware of a subject's pure-tone behavioral thresholds. As indicated above, in the majority of cases in both groups, pure-tone behavioral thresholds were available only on follow-up.

Owing to equipment limits, maximum stimulus intensities for ABR testing were limited to 100 dB nHL for 500 Hz, 95 dB nHL for 2000 Hz, and 90 dB

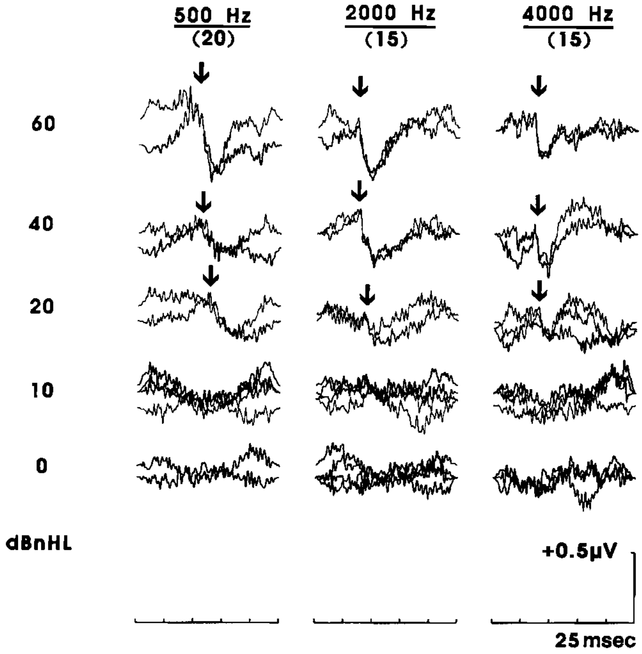

Figure 1. ABRs to brief tones in notched noise recorded from a 21-mo-old subject with normal hearing. Pure-tone behavioral thresholds, obtained at age 24 mo, are shown in parentheses. Traces judged to contain a replicable response are identified by the arrows, which also indicate the approximate location of ABR wave V or the V-to-V′ transition. ABR thresholds were judged to be 20 dB nHL for each of the three frequencies. Waveforms are plotted with positivity at the vertex represented as an upward deflection.

nHL for 4000 Hz. Maximum intensities for behavioral testing were 110 dB HL for the three frequencies. In cases where "no response" was obtained at the maximum equipment intensity, a threshold was arbitrarily assigned as being 10 dB above the maximum.

Threshold difference measurements were calculated by subtracting the pure-tone behavioral thresholds (in dB HL) from the ABR thresholds (in dB nHL). Threshold results were analyzed using descriptive statistics, frequency distributions, linear regressions, and Student's *t*-tests. Results were considered significant if $p < 0.01$. Owing to incomplete repeated measures (and therefore missing data, see Table 2), the statistical significance of differences between means involving different stimulus frequencies, as well as data combined across frequencies, were not assessed.

RESULTS

Overall, 220 ABR/behavioral threshold assessments were obtained from the 88 infants and young children. Seventy-three of these assessments were obtained for 500 Hz, 96 for 2000 Hz, and 51 for 4000 Hz. Most of these ABR thresholds were obtained for children aged under 4 yr (see Table 2).

TABLE 3. Tone-ABR thresholds and detectability for normal-hearing group[a]

	Frequency (Hz)		
	500	2000	4000
Mean threshold (dB nHL)	23.6	12.9	12.6
SD (dB)	9.9	9.0	8.1
N	25	28	23
Detectability (in percent):			
≤10 dB nHL	12	50	52
≤20 dB nHL	52	96	100
≤30 dB nHL	92	100	100
≤40 dB nHL	100	100	100

[a] *Results from group with bilateral normal hearing, with data from only one ear per subject included.*

Figure 1 shows the ABRs to 500, 2000, and 4000 Hz tones in notched noise recorded from a 21-mo-old subject with normal hearing whose results are typical of her group. Vertex-positive waves V followed by vertex-negative waves V′ are clearly present to the three tones presented at 60, 40, and 20 dB nHL. The locations of the waves V (and the judges' rating of "present response") are indicated by the arrows. The ABR thresholds (20 dB nHL) are within 5 dB of her behavioral pure-tone thresholds (indicated at the top of the figure, obtained at age 24 mo).

Mean thresholds (in dB nHL) and response detectability statistics for the ABRs from the normal-hearing ears are presented in Table 3. The mean ABR thresholds for these infants and young children are similar to and slightly better (lower) than those previously presented for adult subjects (Stapells et al, 1990). The response detectability results are also similar between the adult and infant/child groups, suggesting no differences in ABR detectability for infants, young children, and adults. Over 90% of the normal-hearing group showed ABRs to 30 dB nHL 500 Hz tones and to 20 dB nHL 2000 and 4000 Hz tones. The mean ABR threshold for 500 Hz is about 10 dB higher than for 2000 and 4000 Hz. Owing to incomplete repeated measures and therefore missing data, the statistical significance of this and other frequency-related differences were not assessed.

Brain stem response waveforms obtained for the left ear of a 15-mo-old subject with a bilateral sensorineural hearing loss are shown in Figure 2. Location of waves V (and the judges' rating of "present response") are indicated by the arrows. The ABR thresholds (60, 40, and 60 dB nHL for 500, 2000, and 4000 Hz, respectively) are within 5 dB of his pure-tone behavioral thresholds (reliably obtained at age 30 mo) of 55, 35, and 60 dB HL for 500, 2000, and 4000 Hz.

The relationship of the pure-tone behavioral

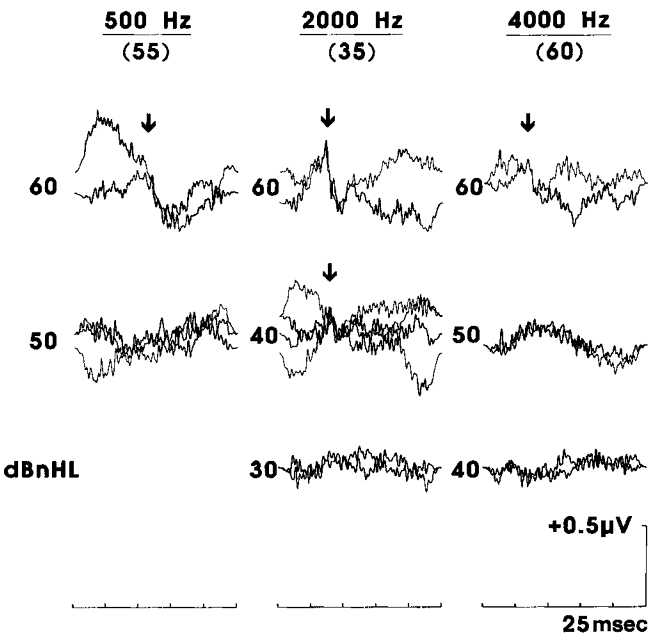

Figure 2. ABRs to brief tones in notched noise recorded from a 15-mo-old subject with a sensorineural hearing loss. Pure-tone behavioral thresholds, obtained at age 30 mo, are shown in parentheses. ABR thresholds were judged to be 60 dB nHL at 500 Hz, 40 dB nHL at 2000 Hz, and 60 dB nHL at 4000 Hz, all within 5 dB of the pure-tone behavioral thresholds. Stimulus intensities, in dB nHL, are plotted to the left of each waveform.

thresholds to the ABR thresholds obtained using the tones in notched-noise technique is illustrated for all ears in the graphs shown in Figure 3. Data points in these scatterplots are identified as to their hearing group (normal or sensorineural loss) and age (at time of ABR) group. With only a few exceptions, the ABR to tones in notched-noise technique provided reasonably accurate estimates of pure-tone behavioral sensitivity for all frequencies. The average (±1 SD) ABR minus behavioral threshold difference is 1.7 ± 13.1 dB (average across both hearing groups and all three frequencies), with a median difference of 0 dB. Results for normal and SNHL ears are similar, with overall threshold differences (average across three frequencies) of 1.5 ± 12.1 dB for the normal-hearing ears and 1.8 ± 13.7 dB for the SNHL ears. If the direction of the ABR minus behavioral threshold difference is not considered (i.e., if we take the absolute value of the difference score), the ABR estimated, on average, within 10.3 ± 8.2 dB of behavioral threshold. Table 4 compares the mean threshold difference scores for the normal-hearing and SNHL ears and for the three frequencies.

In total, 98% of the ABR thresholds were within 30 dB of the behavioral thresholds, 93% were within 20 dB, 80% were within 15 dB, and 66% were within 10 dB. Of the 43 cases where ABR/behavioral thresholds differed by greater than 15 dB, 26 were ABR overestimations (i.e., 12% of cases showed ABR 15 dB or greater overestimations of behavioral threshold). In only four threshold estimations (of a total of 220), all for 500 Hz, the ABR threshold to tones in notched noise overestimated the pure-tone behavioral threshold by greater than 30 dB. One of these >30 dB overestimations was due to the 30 dB nHL minimum intensity for 500 Hz (the 500 Hz pure-tone behavioral threshold was −5 dB HL; the 500 Hz ABR "threshold" was 30 dB nHL or better). If results are excluded where no-response was recorded for either ABR or behavioral measures, the above detectability rates improved such that 74% of the ABR thresholds are now within 10 dB of the behavioral thresholds, and only one difference score is greater than 30 dB.

The ABR threshold estimates appear to be equally accurate across the ages (at time of ABR) spanned by the subjects participating in this study. No significant relationship was found between the ABR minus behavioral threshold difference and the age at ABR evaluation (500 Hz: $r = 0.05$, df = 71, $p > 0.1$; 2000 Hz: $r = 0.18$, df = 94, $p > 0.05$; 4000 Hz: $r = 0.07$, df = 49, $p > 0.1$).

Table 5 (top) presents the results of the linear regression analyses performed on the data for all ears (normal and SNHL) for the ABR (Y) versus pure-tone behavioral (X) thresholds. These results show the same pattern as the threshold difference scores shown in Table 4. The high (≥0.94) correlation coefficients at each frequency indicate the good correspondence between the two thresholds, whereas the near unity (0.88–0.92 dB/dB) slopes indicate similar changes in both measures over a wide range of hearing loss. On the bottom of Table 5 are shown the results of the linear regression analyses when all no-response values have been removed. The primary change is to bring the slopes closer to unity and decrease the Y intercept. That is, the inclusion of the higher no-response levels for behavioral (120 dB HL) compared with ABR (100–110 dB nHL) results had distorted the slopes of the functions shown on the top of Table 5, making them less than unity.

The effect of "flat" versus "sloping" audiometric configuration was investigated next by dividing the ears with into three groups: (i) reverse slope SNHL (low-frequency behavioral thresholds at least 21 dB worse than high-frequency thresholds), $N = 4$; (ii) flat configuration (500 to 4000 Hz behavioral thresholds all within 20 dB of each other, including normal ears), $N = 96$; and (iii) high-frequency (HF) sloping SNHL (high-frequency behavioral thresholds at least 21 dB worse than low-frequency thresholds),

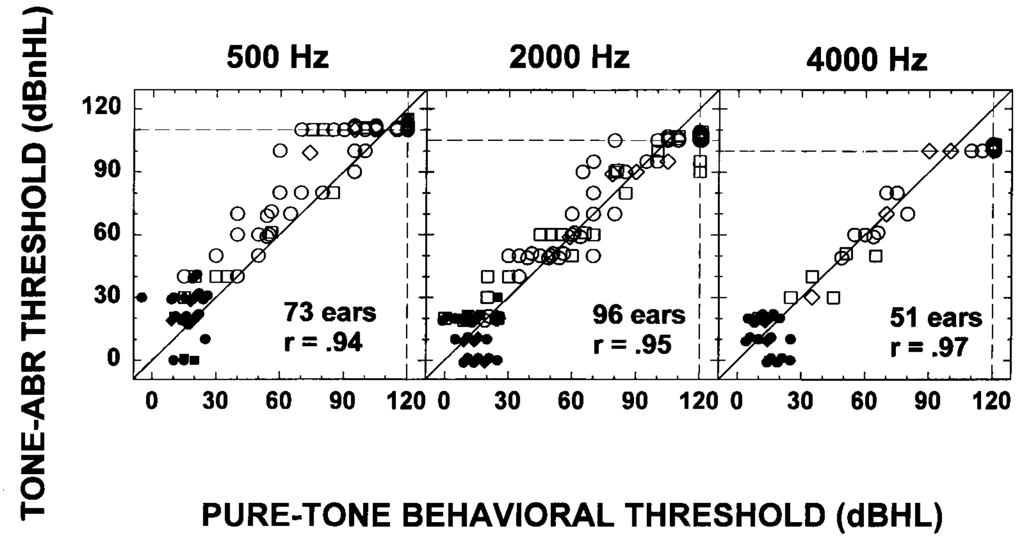

Figure 3. Threshold estimation using the ABR to 500 Hz (left), 2000 Hz (middle), and 4000 Hz (right) tones presented in notched noise. Results for normal-hearing (filled symbols) and sensorineural-impaired (open symbols) ears are plotted with three age ranges (at time of ABR) identified: 0–6 mo, diamonds; 7–48 mo, circles; 49 mo or greater, squares. Shown also are the correlation coefficients for each frequency across all subjects and the number of ears involved. Dashed lines (- - - - -) indicate the no-response range for each frequency and test, equivalent to the equipment maximum output plus 10 dB. Points plotted ≥ the dashed line indicate no-response for the measure. Points with multiple subjects have symbols offset (±1 dB per subject) to show clearly the overlapping data. Diagonals (solid lines) represent perfect ABR/behavioral threshold correspondence and are not regression lines.

TABLE 4. Difference scores (dB): tone-ABR threshold (dB nHL) minus pure-tone behavioral threshold (dB HL)

	Frequency (Hz)		
	500	2000	4000
Normal-hearing ears:			
Mean (dB)	6.8	−0.9	−1.3
SD	11.5	11.8	11.7
SNHL ears:			
Mean (dB)	9.6	−0.2	−6.8
SD	13.4	12.0	11.0
All ears (normal and SNHL):			
Mean (dB)	8.6	−0.4	−4.3
SD	12.8	11.5	12.1

TABLE 5. Results of linear regression analyses[a] for each frequency: All ears (normal-hearing and SNHL)

	Frequency (Hz)		
	500	2000	4000
All data:			
Y intercept, dB nHL	13.11	6.27	3.22
Slope	0.92	0.88	0.85
Standard error of regression (dB)	12.50	10.95	9.75
Correlation coefficient (*r*)	0.94*	0.95*	0.97*
Number of ears	73	96	51
Excluding ABR or behavioral "No response":			
Y intercept, dB nHL	11.02	3.61	1.30
Slope	0.95	0.96	0.92
Standard error of regression (dB)	11.40	10.76	10.11
Correlation coefficient (*r*)	0.91*	0.93*	0.91*
Number of ears	52	76	39

[a] *X = pure-tone behavioral threshold (dB HL); Y = tone-ABR threshold (dB nHL).*

* $p < 0.001$ (one-tailed).

$N = 44$. Across all three frequencies, high correlations remained between the ABR and behavioral thresholds (flat: $r = 0.91$; HF sloping: $r = 0.88$; reverse slope: too few data) and with no-response data excluded, slopes remained near unity. Differences between the ABR minus behavioral threshold difference scores for the three audiometric configurations were small and clinically insignificant (reverse slope: 8.8 ± 2.5 dB; flat: 0.7 ± 13.4 dB; HF sloping: 3.6 ± 14.5 dB), with these differences even smaller when no-response results were removed (reverse slope: 8.8 ± 2.5 dB; flat: 6.8 ± 10.4 dB; HF sloping: 2.1 ± 11.2 dB). Results separated for the three frequencies showed similar patterns, with no clear or statistically significant differences in the ABR minus behavioral threshold difference scores (no-response results excluded) between the flat and HF sloping configurations for 500 Hz (flat: 11.6 ± 11.9 dB; HF sloping: 10.7 ± 10.2 dB; $t = 0.17$, df = 24, $p > 0.1$), 2000 Hz (flat: 5.2 ± 9.2 dB; HF sloping: 1.8 ± 10.5 dB; $t = 1.17$, df = 45, $p > 0.1$), or 4000 Hz (flat: 0.6 ± 4.2 dB; HF sloping: −6.7 ± 8.2 dB; $t = 2.00$, unequal variances adjusted df = 7.7, $p > 0.1$).

In clinical practice, ABR threshold(s) are used to estimate pure-tone behavioral thresholds. Presented below are equations for each frequency that provide these predictions from tone-ABR thresholds. The equations are derived from linear regression analyses of this study's data for all subjects (normal and impaired hearing), with no-response results excluded:

500 Hz: Behavioral threshold (dB HL) = $-3.25 + (0.87 * \text{ABR threshold, dB nHL}) \pm 10.96$ (SE, dB)

2000 Hz: Behavioral threshold (dB HL) = $+1.82 + (0.91 * \text{ABR threshold, dB nHL}) \pm 10.46$ (SE, dB)

4000 Hz: Behavioral threshold (dB HL) = $+4.12 + (0.90 * \text{ABR threshold, dB nHL}) \pm 10.00$ (SE, dB)

DISCUSSION

The results of this study indicate that reasonably accurate estimates of 500, 2000, and 4000 Hz pure-tone behavioral thresholds in infants and young children can be obtained by recording the auditory brain stem response to brief tones presented in notched masking noise. In this study, the majority (66–74%) of the tone-ABR thresholds were within 10 dB of the subjects' pure-tone behavioral thresholds, and 93% were within 20 dB. These results are similar to results previously reported for this technique in adults with normal hearing (Picton et al, 1979; Purdy et al, 1989; Stapells et al, 1990) and adults with hearing loss (Picton et al, 1979; Stapells et al, 1990; Munnerley et al, 1991).

No differences were seen in the ABR minus behavioral threshold difference scores between the ears with normal hearing and those with SNHL. This is in contrast to previous studies in adults which have indicated that differences between brief-tone ABR and pure-tone behavioral thresholds are reduced in subjects with SNHL compared to subjects with normal hearing (e.g., Picton et al, 1979; Stapells et al, 1990). This has been suggested to be due primarily to the influence (i.e., reduction of threshold) of temporal integration on pure-tone behavioral thresholds of subjects with normal hearing and the lack of such an influence for subjects with SNHL (Stapells et al, 1990). This lack of difference between pediatric subjects with normal hearing and SNHL may suggest poorer temporal integration in the pediatric population or may reflect attentional and motivational effects and the less reliable behavioral results seen in these young subjects (for reviews, see Werner & Rubel, 1992; Wilson & Thompson, 1984).

More generally, the results of this study complement and confirm the results of the large number of studies which have indicated that the ABRs to 500 to 4000 Hz brief tones (masked or nonmasked) are recordable down to acceptably low intensities and provide reasonable estimates of behavioral thresholds (e.g., Beattie & Boyd, 1985; Davis & Hirsh, 1979; Davis et al, 1985; Foxe & Stapells, 1993; Gorga et al, 1988; Gorga, Kaminski, Beauchaine, & Bergman, 1993; Hayes & Jerger, 1982; Hyde et al, 1987; Kileny & Magathan, 1987; Klein, 1983, 1984; Kodera et al, 1977; Kramer, 1992; McGee & Clemis, 1980; Munnerley et al, 1991; Picton et al, 1979; Purdy et al, 1989; Purdy & Abbas, 1989; Stapells & Picton, 1981; Stapells et al, 1990, 1994; Stapells & Ruben, 1989; Suzuki & Yamane, 1982; Suzuki et al, 1984; Suzuki et al, 1977). They are in contrast to a small number of studies that have indicated unsatisfactory results with tone-evoked ABRs, particularly at 500 Hz.

The results of the present study in infants and young children should lay to rest concerns about the applicability of previous adult tone ABR studies' results to the pediatric population. Many of the adult studies employed a near-40/sec stimulus rate (e.g., Picton et al, 1979; Purdy et al, 1989; Stapells et al, 1990; Munnerley et al, 1991) and must have contained both ABR wave V and the 40 Hz steady-state response (Galambos et al, 1981; Stapells, Linden, Suffield, Hamel, & Picton, 1984). Because infants and young children do not show the response amplitude enhancements seen in adults when stimuli are presented at about 40/sec (Stapells, Galambos, Costello & Makeig, 1988; Suzuki & Kobayashi, 1984), the possibility that the adult tone-ABR studies, especially for 500 Hz stimuli, would not be applicable to infants has recently been suggested (Picton, 1991; Picton, Champagne & Kellett, 1992; Stapells et al, 1990). In contrast to this concern, however, the majority (92 to 100%) of the infants and young children with normal hearing in the present study produced clear ABRs to the tones at acceptably low stimulus intensities (≤30 dB nHL), and the ABR thresholds to tones in notched noise accurately estimated the pure-tone behavioral thresholds of the infants and children with SNHL. This was true for 500 Hz as well as for 2000 and 4000 Hz. The ABR to tones in notched-noise technique is thus applicable to pediatric clinical populations.

ABR thresholds to 500 Hz brief tones are elevated by about 10 dB compared to the thresholds for higher frequency stimuli. A −10 dB correction factor might therefore be appropriate when evaluating this frequency. Alternatively, the regression equations provided at the end of the "Results" section may be used to predict behavioral thresholds. In this study, the normal-hearing infants' mean 500 Hz ABR threshold was 23.6 dB nHL (48 dB pe SPL), compared with 12.9 dB nHL (39.0 dB pe SPL) for 2000

Hz and 12.6 dB nHL (41.6 dB pe SPL) for 4000 Hz. The 2000 and 4000 Hz normative results are similar to ours (Stapells et al, 1990) and others' previous studies (e.g., Purdy et al, 1989; Suzuki et al, 1984). The 500 Hz ABR normal thresholds are similar to our previous study in adults (Stapells et al, 1990), but are about 10 dB worse than others have reported (Purdy et al, 1989; Suzuki et al, 1984). We are currently compiling normative brief-tone ABR results in a larger sample of infants.

In general, brain stem responses to 500 Hz brief tones require more experience to recognize than do ABRs to higher frequency stimuli. These responses to low-frequency stimuli usually do not demonstrate the sharper peaks seen in response to 2000 or 4000 Hz brief tones. Because of this, they are also more susceptible to background electrical noise, whether of patient or environmental origin. This may be the reason for the one 500 Hz ABR overestimation of greater than 30 dB seen in this study (excluding data involving maximum or minimum stimulus intensities). In order to adequately assess 500 Hz thresholds using the ABR, patients must be sleeping quietly, clinicians must be experienced with these responses, and a sufficient number of trials and replications must be averaged to ensure low residual electrical noise levels in the waveforms. Objective signal-to-noise measures (e.g., Elberling & Don, 1984; Picton et al, 1983) may help in this regard, although no studies of their application to tone-evoked ABRs have been published.

The clinical origin of the present study's infants and children with hearing loss likely added some variability to results as well as placing limitations on the number of thresholds and the minimum intensities tested. Further, the follow-up required for this and any study involving infants adds variability and inaccuracies often associated with the time lag between the ABR and behavioral measures.

One set of limitations is related to the behavioral audiometry. Because many of the behavioral audiograms were obtained at a later age, occasionally as much as 1 to 2 yr after the ABR assessment, there is the possibility that hearing thresholds worsened during this time. Other possible problems related to the different times for behavioral audiometry include: (i) variable procedures and criteria for behavioral audiometry (related to differing developmental levels), and (ii) differing middle ear status not revealed by acoustic immittance results or history (i.e., subclinical). Finally, it is likely that some of the infants' follow-up behavioral thresholds were still higher than adult levels due to their immaturity (i.e., in the 6- to 24-mo age range) (Wilson & Thompson, 1984). Keeping in mind these issues, the mean ABR behavioral time difference was 2.2 mo. Thus, for most subjects, results for both measures were obtained relatively close to each other. Further, we often had more than one set of behavioral results to confirm the reliability and stability of the behavioral results. Finally, infants with questionable or unobtainable acoustic immittance results were excluded.

Another set of limitations related to the clinical origin of the group with SNHL were the procedures necessitated by the need for specific clinical information. Because 2000 Hz thresholds were deemed most relevant, they were almost always obtained first, to the detriment of 500 and 4000 Hz. Thus, there are fewer data for these latter frequencies. We were careful, however, to ensure only data from quiet and sleeping subjects were included. Thus, some 500 and 4000 Hz data were excluded because the subject awoke during testing of these frequencies. Another limitation of these clinically obtained data concern our minimum intensities. Because of time constraints and need for clinical efficiency, we did not assess below 30 dB nHL for 500 Hz or below 20 dB nHL for 2000 and 4000 Hz in the group with SNHL. This affected results for a total of only nine data points (500 Hz: $N = 1$; 2000 Hz: $N = 7$; 4000 Hz: $N = 1$), but could have contributed to the slightly less-than-unity slopes of the regression lines. Finally, there is an advantage to these clinical results: the subjects with SNHL probably slept quieter and longer because of their chloral hydrate-induced sleep and/or because of their being sleep deprived by parents anxious to obtain necessary clinical information. The infant and young children in the group with normal hearing were required to sleep naturally. They did not receive chloral hydrate and their parents did not always sleep deprive them for the study.

Considering the limitations outlined above, the results of the present study are very encouraging: the ABR to tones in notched-noise technique provided reasonably accurate estimations of these children and infants' pure-tone behavioral thresholds. Although this study did not compare these results to those obtained without notched-noise masking, previous studies have indicated the masking to be particularly useful for assessing hearing loss with rising or sloping configurations (Picton, 1978; Picton et al, 1979; Stapells et al, 1994). Because one does not know in advance the slope of an infant's audiometric configuration, notched-noise masking would be used for all cases.

There are likely to be improvements in techniques to obtain frequency-specific evoked potential thresholds in infants and young children. Nonlinear gating functions (e.g., Blackman window) improve the frequency specificity of the brief tones and may, therefore, improve the frequency specificity of the ABR elicited by these brief tones (Gorga & Thornton, 1989). ABR data supporting this suggestion, however, are currently lacking, and a recent paper by Purdy and Abbas (1989) reported no differences for linear versus Blackman tones. The use of such stimuli and the current availability of filters with very steep rejection slopes may allow for improvements in the notched-noise masker (e.g., notch width, noise intensity). Although not widely implemented on commercial equipment, notched-noise masking could be easily incorporated by equipment manufacturers if clinicians demanded this feature. Additionally, objective response measures are now available on commercial clinical equipment and should help in making decisions concerning response presence/absence, although research is required for their use with tone-evoked ABRs. Finally, although not reliably present in infants using 40/sec rates (Stapells et al, 1988; Suzuki & Kobayashi, 1984), brain stem steady-state responses to amplitude-modulated tones can be recorded in infants if very rapid (80 to 100/sec) modulation rates are used, allowing the use of rapid and objective, frequency-based, response measures (Aoyagi, Kiren, Kim, Suzuki, Fuse & Koike, 1993; Levi, Folsom, & Dobie, 1993).

In summary, the present study suggests that, using the ABR to brief tones in notched noise, reasonably accurate estimates of 500, 2000, and 4000 Hz pure-tone behavioral thresholds may be obtained in infants and young children with either normal hearing or sensorineural hearing loss. In the present study, 93% of the ABR thresholds were within 20 dB of the behavioral thresholds, and 80% were within 15 dB. No differences were seen as a result of age at ABR (1 week post-term to 8 yr) or as a result of audiometric configuration (rising, flat, sloping). Provided clinicians use appropriate protocols and have reasonable experience with tone-evoked ABRs, the technique is ready for clinical use, and should provide results that are more accurate than click-evoked ABR threshold results. Click ABR/behavioral threshold regression equations, in addition to their lack of frequency specificity, show lower correlations, larger standard errors, and lower slopes (i.e., less than unity) compared with results for tone-evoked ABRs (Stapells et al, 1994). After several years of using both tone- and click-evoked ABR techniques in our clinic, we no longer use the click-evoked ABR for threshold estimations. Instead, we rely on ABR thresholds for brief tones in notched noise to estimate hearing sensitivity in infants and young children.

ACKNOWLEDGMENTS:

This work was supported by United States Public Health Service, National Institute for Deafness and Other Communication Diseases (NIDCD) Cinical Center Grant 8 P50 DC00223, and by NICHD Mental Retardation Research Center Grant HD01799. Brett Martin was supported by a Graduate Research Assistantship from the City University of New York (CUNY).

Presented at the annual convention of the American Speech-Language-Hearing Association, San Antonio, TX, November 22, 1992, and at the 16th midwinter research meeting of the Association for Research in Otolaryngology, St. Petersburg Beach, FL, February 8, 1993.

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Received May 5, 1994; accepted January 11, 1995

REFERENCES

Aoyagi, M., Kiren, T., Kim, Y., Suzuki, Y., Fuse, T., & Koike, Y. (1993). Optimal modulation frequency for amplitude-modulation following response in young children during sleep. *Hearing Research*, *65*, 253–261.

Beattie, R. C., & Boyd, R. L. (1985). Early/middle evoked potentials to tone bursts in quiet white noise, & notched noise. *Audiology*, *24*, 406–419.

Davis, H., & Hirsh, S. K. (1976). The audiometric utility of the brain stem response to low-frequency sounds. *Audiology*, *15*, 181–195.

Davis, H., & Hirsh, S. K. (1979). A slow brain stem response for low-frequency audiometry. *Audiology*, *18*, 445–461.

Davis, H., Hirsh, S. K., Turpin, L. L., & Peacock, M. E. (1985). Threshold sensitivity, and frequency specificity in auditory brainstem response audiometry. *Audiology*, *24*, 54–70.

Elberling, C., & Don, M. (1984). Quality estimation of averaged auditory brainstem responses. *Scandinavian Audiology*, *13*, 187–197.

Foxe, J. J., & Stapells, D. R. (1993). Normal infant and adult auditory brainstem responses to bone-conducted tones. *Audiology*, *32*, 95–109.

Galambos, R., Makeig, S., & Talmachoff, P. J. (1981). A 40-Hz auditory potential recorded from the human scalp. *Proceedings of the National Academy of Sciences U. S. A*, *78*, 2643–2647.

Gorga, M. P., & Thornton, A. R. (1989). The choice of stimuli for ABR measurements. *Ear and Hearing*, *10*, 217–230.

Gorga, M. P., Kaminski, J. R., Beauchaine, K. A., & Jesteadt, W. (1988). Auditory brainstem responses to tone bursts in normally hearing subjects. *Journal of Speech and Hearing Research*, *31*, 87–97.

Gorga, M. P., Kaminski, J. R., Beauchaine, K. L., & Bergman, B. M. (1993). A comparison of auditory brain stem response thresholds, & latencies elicited by air-, & bone-conducted stimuli. *Ear and Hearing*, *14*, 85–94.

Hayes, D., & Jerger, J. (1982). Auditory brainstem response (ABR) to tone pips: Results in normal and hearing-impaired subjects. *Scandinavian Audiology*, *11*, 133–142.

Hyde, M. L. (1985). Frequency-specific BERA in infants. *Journal of Otolaryngology Supplement*, *14*, 19–27.

Hyde, M. L., Matsumoto, N., & Alberti, P. W. (1987). The normative basis for click and frequency-specific BERA in high-risk infants. *Acta Oto-Laryngologica (Stockholm)*, *103*, 602–611.

Jerger, J. (1970). Clinical experience with impedance audiometry. *Archives of Otolaryngology*, *92*, 311–324.

Kileny, P. R., & Magathan, M. G. (1987). Predictive value of ABR in infants and children with moderate to profound hearing impairments. *Ear and Hearing*, *8*, 217–221.

Klein, A. J. (1983). Properties of the brain-stem response slow-wave component. I. Latency, amplitude, and threshold sensitivity. *Archives of Otolaryngology*, *109*, 6–12.

Klein, A. J. (1984). Frequency and age-dependent auditory evoked potential thresholds in infants. *Hearing Research*, *16*, 291–297.

Kodera, K., Yamane, H., Yamada, O., & Suzuki, J-I. (1977). Brain stem response audiometry at speech frequencies. *Audiology*, *16*, 469–479.

Kramer, S. J. (1992). Frequency specific auditory brainstem responses to bone-conducted stimuli. *Audiology*, *31*, 61–71.

Laukli, E. (1983). High-pass and notch noise masking in suprathreshold brainstem response audiometry. *Scandinavian Audiology*, *12*, 109–115.

Laukli, E., Fjermedal, I., & Mair, I. W. S. (1988). Low-frequency auditory brainstem response threshold. *Scandinavian Audiology*, *17*, 171–178.

Levi, E. C., Folsom, R. C., & Dobie, R. A. (1993). Amplitude-modulation following response (AMFR): Effects of modulation rate, carrier frequency, age, and state. *Hearing Research*, *68*, 42–52.

Marchant, C. D., McMillan, P. M., Shurin, P. A., Turczyk, V. A., Feinstein, J. C., & Panek, D. M. (1986). Objective diagnosis of otitis media in early infancy by tympanometry and ipsilateral acoustic reflex thresholds. *Journal of Pediatrics*, *109*, 590–595.

McGee, T. J., & Clemis, J. D. (1980). The approximation of audiometric thresholds by auditory brainstem responses. *Otolaryngology, Head and Neck Surgery*, *88*, 295–303.

Munnerley, G. M., Greville, K. A., Purdy, S. C., & Keith, W. J. (1991). Frequency-specific auditory brainstem responses relationship to behavioral thresholds in cochlear-impaired adults. *Audiology*, *30*, 25–32.

Pickles, J. O. (1986). *An introduction to the physiology of hearing* (2nd ed). London: Academic Press.

Picton, T. W. (1978). The strategy of evoked potential audiometry. In S. E. Gerber, & G. T. Mencher (Eds.), *Early diagnosis of hearing loss* (pp. 297–307). New York: Grune & Stratton.

Picton, T. W. (1991). Clinical usefulness of auditory evoked potentials: A critical evaluation. *Journal of Speech-Language Pathology and Audiology*, *15*, 3–29.

Picton, T. W., & Durieux-Smith, A. (1988). Auditory evoked potentials in the assessment of hearing. *Neurologic Clinics*, *6*, 791–808.

Picton, T. W., Ouellette, J., Hamel, G., & Smith, A. D. (1979). Brainstem evoked potentials to tone pips in notched noise. *Journal of Otolaryngology*, *8*, 289–314.

Picton, T. W., Linden, R. D., Hamel, G., & Maru, J. T. (1983). Aspects of averaging. *Seminars in Hearing*, *4*, 327–340.

Picton, T. W., Champagne, S. C., & Kellett, A. J. C. (1992). Human auditory evoked potentials recorded using maximum length sequences. *Electroencephalography and Clinical Neurophysiology*, *84*, 90–100.

Purdy, S. C., & Abbas, P. J. (1989). Auditory brainstem response audiometry using linearly and Blackman-gated tone bursts. *ASHA*, *31*, 115–116.

Purdy, S. C., Houghton, J. M., Keith, W. J., & Greville, K. A. (1989). Frequency-specific auditory brainstem responses. Effective masking levels and relationship to behavioural thresholds in normal hearing adults. *Audiology*, *28*, 82–91.

Sohmer, H., & Kinarti, R. (1984). Survey of attempts to use auditory evoked potentials to obtain an audiogram. *British Journal of Audiology*, *18*, 237–244.

Stapells, D. R. (1984). *Studies in evoked potential audiometry.* Unpublished doctoral dissertation, University of Ottawa, Ottawa, Ontario, Canada.

Stapells, D. R. (1989). Auditory brainstem response assessment of infants and children. *Seminars in Hearing*, *10*, 229–251.

Stapells, D. R., & Picton, T. W. (1981). Technical aspects of brainstem evoked potential audiometry using tones. *Ear and Hearing*, *2*, 20–29.

Stapells, D. R., & Ruben, R. J. (1989). Auditory brainstem responses to bone-conducted tones in infants. *Annals of Otology, Rhinology and Laryngology*, *98*, 941–949.

Stapells, D. R., Linden, D., Suffield, J. B., Hamel, G., & Picton, T. W. (1984). Human auditory steady state potentials. *Ear and Hearing*, *5*, 105–113.

Stapells, D. R., Galambos, R., Costello, J. A., & Makeig, S. (1988). Inconsistency of auditory middle latency and steady-state responses in infants. *Electroencephalography and Clinical Neurophysiology*, *71*, 289–295.

Stapells, D. R., Picton, T. W., Durieux-Smith, A., Edwards, C. G., & Moran, L. M. (1990). Thresholds for short-latency auditory-evoked potentials to tones in notched noise in normal-hearing and hearing-impaired subjects. *Audiology*, *29*, 262–274.

Stapells, D. R., Picton, T. W., & Durieux-Smith, A. (1994). Electrophysiologic measures of frequency-specific auditory function. In J. T. Jacobson (Ed.), *Principles and applications in auditory evoked potentials* (pp. 251–283). Needham Heights, MA: Allyn & Bacon.

Stockard, J. E., Stockard, J. J., & Coen, R. W. (1983). Auditory brain stem response variability in infants. *Ear and Hearing*, *4*, 11–23.

Suzuki, J-I., & Yamane, H. (1982). The choice of stimulus in the auditory brainstem response test for neurological and audiological examinations. *Annals of the New York Academy of Sciences*, *82*, 731–736.

Suzuki, J-I., Kodera, K., & Yamada, O. (1984). Brainstem response audiometry in newborns and hearing-impaired infants. In A. Starr, C. Rosenberg, M. Don, & H. Davis (Eds.), *Sensory evoked potentials. 1. An international conference on standards for auditory brainstem response (ABR) testing* (pp. 85–93). Milan, Italy: CRS Amplifon.

Suzuki, T., & Kobayashi, K. (1984). An evaluation of 40-Hz event-related potentials in young children. *Audiology*, *23*, 599–604.

Suzuki, T., Hirai, Y., & Horiuchi, K. (1977). Auditory brainstem responses to pure tone stimuli. *Scandinavian Audiology*, *6*, 51–56.

Takagi, N., Suzuki, T., & Kobayashi, K. (1985). Effect of tone-burst frequency on fast and slow components of auditory brain-stem response. *Scandinavian Audiology*, *14*, 75–79.

Werner, L. A., & Rubel, E. W. (Eds.) (1992). *Developmental psychoacoustics*. Washington, DC: American Psychological Association.

Wilson, W. R., & Thompson, G. (1984). Behavioral audiometry. In J. Jerger (Ed.) *Pediatric audiology* (pp. 1–44). San Diego: College-Hill Press.

Yamada, O., Yagi, T., Yamane, H., & Suzuki, J-I. (1975). Clinical evaluation of the auditory evoked brain stem response. *Auris-Nasus-Larynx*, *2*, 97–105.