Threshold Estimation by the Tone-Evoked Auditory Brainstem Response: A Literature Meta-Analysis

Évaluation du seuil de la surdité par la méthode des potentiels évoqués auditifs avec stimulus tonal : méta-analyse de la littérature

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Abstract

The goal of the present study was to determine, across a large number of studies and participants, the threshold estimation performance of the air-conducted tone-evoked auditory brainstem response (ABR) for adult and infant/child groups with either normal hearing or sensorineural hearing loss (SNHL). Overall, 32 studies were included in this meta-analysis, representing results from a total of 1,203 individual participants (i.e., 524 adults or older children, 679 infants or young children; 815 individuals with normal hearing; and 388 individuals with SNHL). Results indicate that tone-evoked ABR thresholds in individuals with normal hearing are typically 10 to 20 dB nHL. Tone-ABR thresholds in participants with SNHL are typically 5 to 15 dB higher than pure-tone behavioural thresholds in adult participants and from 10 dB lower to 10 dB higher than pure-tone behavioural thresholds in infants and young children. Importantly, threshold results are quite consistent across studies, and 95% confidence intervals are no larger than ±5 dB. These results support the recommendation by current guidelines that tone-evoked ABR thresholds be used to guide the initial fitting of amplification in very young infants.

Abrégé

La présente étude vise à déterminer, parmi un grand nombre d'études et de participants, les seuils estimatifs des potentiels évoqués auditifs en réponse à un stimulus tonal par conduction aérienne chez des groupes d'adultes et de poupons/enfants qui ont une audition normale ou qui sont atteints d'une surdité de perception. Dans l'ensemble, 32 études ont été incluses dans la présente méta-analyse, ce qui représente les résultats produits par 1 203 participants (à savoir 524 adultes ou enfants plus âgés et 679 poupons ou jeunes enfants, 815 personnes ayant une ouïe normale et 388 personnes atteintes d'une surdité de perception). Les résultats indiquent que les seuils estimatifs des potentiels évoqués auditifs en réponse à un stimulus tonal chez les gens ayant une ouïe normale sont généralement de 10 à 20 dB nHL. Les seuils des potentiels évoqués auditifs en réponse à un stimulus tonal chez les participants atteints d'une surdité de perception s'établissent en moyenne de 5 à 15 dB au-delà des seuils audiométriques des sons purs chez les adultes participants et entre 10 dB en-deçà et 10 dB au-delà des seuils audiométriques des sons purs chez les bébés et les jeunes enfants. Il est important de noter que les résultats des seuils sont assez uniformes dans toutes les études, et 95 % des intervalles de confiance ne sont pas plus grands que ±5 dB. Ces résultats correspondent aux lignes directrices actuelles selon lesquelles les seuils des potentiels évoqués auditifs en réponse à un stimulus tonal peuvent servir à guider le réglage initial de l'amplification chez les très jeunes enfants.

Key words: auditory brainstem response, tones, threshold estimation, sensorineural hearing loss, meta-analysis

Recent research (Moeller, 2000; Yoshinaga-Itano, Sedey, Coulter, & Mehl, 1998) emphasizes the importance of early identification and intervention (i.e., by age 6 months) for congenital hearing loss. In this era of very early identification of hearing loss, the auditory brainstem response (ABR) is the only measure that can provide reliable and accurate thresholds in infants under five to six months of age (Gravel, 1992; The Pediatric Working Group, 2000).

The ABR to brief tones has been used successfully for threshold estimation purposes since the publications in 1977 by Japanese researchers/clinicians T. Suzuki and colleagues (Suzuki, Hirai, & Horiuchi, 1977) and J.-I. Suzuki and colleagues (Kodera, Yamane, Yamada, & Suzuki, 1977). Around the same time, researchers and clinicians in North America also reported success in estimating the audiogram using the ABR to brief tones (e.g., Davis & Hirsh, 1979; Mitchell & Clemis, 1977; Picton, Ouellette, Hamel, & Smith, 1979).). Despite this early success, and the many subsequent studies supporting the use of the ABR to brief tones to estimate behavioural hearing thresholds in adults, children and infants with normal or impaired hearing, *there remains an impression commonly held by audiologists that the tone-evoked ABR poorly predicts pure-tone behavioural threshold, especially for low frequencies.* Some of this belief stems from a small number of studies which concluded the tone-ABR technique has problems (e.g., Davis & Hirsh, 1976; Laukli, Fjermedal, & Mair, 1988). Many of these "dissenting" studies, however, had technical problems such as using too-high high-pass EEG filter settings (e.g., 100 Hz or higher), obtaining recordings from acoustically and/or electrically noisy environments (e.g., the operating room), or use of other inappropriate recording parameters (e.g., using a contralateral ear recording channel). Importantly, few of these dissenting studies present any group results.

As suggested above, there have been many studies that have investigated the ability of the tone-evoked ABR to estimate behavioural thresholds, in individuals with normal hearing or with hearing loss. Most of these studies concluded the technique works reasonably well. The present paper is not a review of this literature; such reviews, as well as recommended parameters and protocols may be found in our previous papers (Stapells, 2000; Stapells & Oates, 1997; Stapells, Picton, & Durieux-Smith, 1994). Instead, the present study sought to integrate the tone-ABR threshold results available from the many published (as well as some unpublished) studies that meet inclusion criteria. Most studies in the literature have been based on small participant sample sizes (i.e., ≤ 25 participants), although some study samples of moderate size (i.e., 30 to 100 participants) exist. Especially when broken down into results for different frequencies and/or different populations, these sample sizes are too small to establish confidence intervals. The goal of the present study was to determine, across a large number of studies and participants, the threshold estimation performance of the air-conducted tone-evoked ABR for adult and infant/child groups with either normal hearing or sensorineural hearing loss (SNHL). The measures determined were mean thresholds (in dB nHL) for individuals with normal hearing, mean difference score (i.e., tone-ABR threshold in dB nHL minus the pure-tone behavioural threshold in dB HL for individuals with SNHL), standard error of the mean (in dB), and the 95% confidence intervals.

Method

Literature Search

A literature search for all air-conducted (AC) tone-ABR threshold studies was performed via several means: (a) an electronic search using MEDLINE/PUBMED, (b) a search through the subject indexes of the journals relevant to the topic, (c) a search through the author's personal library; and (d) a review of the reference sections of the relevant articles obtained from the above searches.

Inclusion Criteria

To be included in the meta-analysis, studies met all of the following criteria: (a) ABR thresholds were obtained in response to AC brief tones for at least one of 500, 1000, 2000 and/or 4000 Hz; (b) a participant's hearing status was adequately determined, independent of tone-ABR results; and (c) group data were available from the manuscript, such that mean and standard deviation threshold data were available. In some cases, these results were calculated from individual results provided in the articles.

Exclusion Criteria

Studies were excluded from the meta-analysis if any of the following situations occurred: (a) recordings were obtained under inappropriate conditions (e.g., rooms with high ambient noise, such as an operating room) or with inappropriate recording settings (e.g., thresholds from children determined using a contralateral ABR channel), (b) threshold levels for the acoustic stimuli were not referenced to normative behavioural thresholds, or (c) the manuscript did not provide results for groups of participants and such results could not be determined by the present author from any individual's results presented. Three examples of excluded studies are presented in the Appendix.

Participant Groups

Results were broken down in terms of hearing status (i.e., normal hearing vs. hearing loss) and in terms of age (i.e., adults and older children; infants and young children). Specifically, results for the four following groups were determined: (a) adults and older children with normal hearing, (b) adults and older children with sensorineural hearing loss (at least 80% of group must be with SNHL), (c) infants and young children (i.e., most participants under six years of age) with normal hearing, and (d) infants and young children with SNHL.

Measures

After tabulating the mean data, standard deviations, and sample sizes for each study included in this meta-analysis, the following measures were calculated: (a) mean tone-ABR threshold (in dB nHL) for individuals with normal hearing after the results for each study were appropriately weighted for its sample size; (b) mean difference score (i.e., tone-ABR threshold in dB nHL minus the pure-tone behavioural threshold in dB HL) for individuals with SNHL; again appropriately weighted for each study's sample size; (c) standard error of the mean (in dB) for all groups determined by appropriate combination of variances from each study (Glass & Hopkins, 1996); and (d) 95% confidence intervals (in dB nHL or dB difference) for all groups determined from the sample standard error (Glass & Hopkins).

Results

Overall, 32 studies were included in this meta-analysis.

These studies represented the results from a total of 1,203 individual participants: 524 were adults or older children, 679 were infants or young children (most under two years of age), 815 individuals had normal hearing sensitivity, and 388 individuals had SNHL. Detailed results from each study for each of the four participant groups are presented in Tables 1 to 4.

Table 5 summarizes the results for the participants with normal hearing. For the adult participants, mean ABR thresholds range between 11.8 and 20.4 dB nHL for 500, 1000, 2000, and 4000 Hz tones. Their ABR thresholds for 500 Hz tones are about 4 dB higher than those for 1000 Hz tones, which, in turn, are about 3 dB higher than those to 2000 Hz tones. Adults' ABR thresholds for 2000 and 4000 Hz tones are, on average, within 1 to 2 dB of each other. Although these differences are quite small, the lack of overlap of the 500, 1000 and 2000 Hz confidence intervals suggest these small differences are statistically significant.

Table 1. Summary of Studies Reporting Tone-ABR Thresholds (in dB nHL) in Adults With Normal Hearing as a Function of Frequency.

	500 Hz			1000 Hz			2000 Hz			4000 Hz		
Study	*n*	*M*	*SD*	*n*	*M*	*SD*	*n*	*M*	*SD*	*n*	*M*	*SD*
Kodera et al., 1977	10	15.5	3.5	10	16.5	3.9	10	16.5	3.2			
T. Suzuki et al., 1977	20	15.0	8.3	20	12.5	7.2	20	14.5	7.6	20	8.5	5.9
Picton et al., 1979	20	14.0	11.0	20	15.0	16.0	20	14.0	12.0	20	17.0	12.0
Bauch et al., 1980				17	14.4	5.0	17	12.9	5.9	17	13.8	7.4
T. Suzuki et al., 1981	19	19.0	6.6	19	14.7	5.1	19	12.6	8.1	10	11.1	6.6
McDonald & Shimizu, 1981	8	35.0	7.6									
Klein, 1983	30	16.0	9.5	30	14.0	7.0	30	16.0	2.5	30	19.0	7.4
Yamada et al., 1983				7	15.0	4.1						
Beattie et al., 1984	10	27.0	9.5				10	20.0	6.7			
Kavanagh et al., 1984	10	18.0	7.8									
Klein, 1984	10	13.0	5.6							10	12.0	5.3
Gorga et al., 1988	20	34.0	15.6	20	21.0	8.9	20	15.0	7.7	20	9.0	8.3
Palaskas et al., 1989	16	41.7	10.0									
Purdy et al., 1989	20	8.8	4.6	20	8.0	3.6	20	4.4	3.4	20	7.4	5.0
Stapells et al., 1990	20	22.5	12.5	20	16.0	11.4	20	13.5	8.3	20	9.0	8.5
Gorga et al., 1993	10	16.0	8.0	10	20.0	11.0	10	10.0	11.0	10	9.0	4.0
Werner et al., 1993				40	19.3	8.9				40	13.8	8.9
Beattie & Torre, 1997	16	35.0	8.2	16	35.6	7.3						
Sininger et al., 1997	22	11.0	6.0							22	5.0	5.0
Purdy & Abbas, 1989				10	13.5	4.4	10	11.1	4.4	10	13.0	3.8
Wu & Stapells, submitted	10	15.0	8.2				10	14.0	7.4			
Nousak & Stapells, 1999				12	3.3	5.4						

Table 2. Summary of Studies Reporting Tone-ABR Thresholds (in dB nHL) in Infants and Children With Normal Hearing as a Function of Frequency.

	500 Hz			1000 Hz			2000 Hz			4000 Hz		
Study	*n*	*M*	*SD*	*n*	*M*	*SD*	*n*	*M*	*SD*	*n*	*M*	*SD*
Hayes & Jerger, 1982	20	14.5	5.1				20	16.0	5.0			
Yamada et al., 1983				24	16.5	4.0						
J-I Suzuki et al., 1984	14	17.0	4.5	14	18.3	3.5	14	16.0	4.2			
Klein (ages 2-4 wks), 1984	10	22.0	6.2							10	33.0	8.4
Klein (ages 5-12 wks), 1984	10	22.0	11.4							10	23.0	3.7
Klein (ages 13-20 wks), 1984	10	20.0	6.3							10	21.5	4.9
Klein (ages 21-28 wks), 1984	10	15.0	4.6							10	19.0	4.0
Werner et al. (age 3 mos), 1993				32	18.4	8.0				32	11.0	6.2
Werner et al. (age 6 mos), 1993										33	12.7	6.7
Stapells et al., 1995	23	23.6	9.9				23	12.9	9.0	23	12.6	8.1
Sininger et al., 1997	22	16.5	8.0							22	6.0	10.0
Balfour et al., 1998	8	9.3	3.8	8	14.2	5.6	8	5.7	6.4	8	6.1	1.9
Littman (19 mos; males), 1999, unpub	134	21.8	8.1							31	20.2	9.2
Littman (19mos; females), 1999, unpub	108	18.7	9.5							20	20.3	8.9

Table 3. Summary of Studies Reporting Tone-ABR Thresholds (in dB nHL) in Adults With Sensorineural Hearing Loss as a Function of Frequency: Difference Scores (dB).

	500 Hz			1000 Hz			2000 Hz			4000 Hz		
Study	*n*	*M*	*SD*	*n*	*M*	*SD*	*n*	*M*	*SD*	*n*	*M*	*SD*
Kodera et al., 1977	16	11.3	8.0	16	10.9	6.2	16	10.9	6.2			
Picton et al., 1979	4	14.0	11.0	4	15.0	16.0	4	14.0	12.0	4	17.0	12.0
Purdy & Abbas, 1989				15	5.0	9.6	15	0.9	12.3	15	-6.2	8.7
Stapells et al., 1990	20	7.0	7.1	20	1.3	11.7	20	3.0	7.1	20	-1.0	15.4
Munnerley et al., 1991	30	11.9	7.1	30	9.4	8.2	30	9.6	8.7	30	10.4	9.0
Conijn et al., 1993				55	13.9	11.0						
Beattie et al., 1996	15	27.0	15.0	15	24.0	15.0	15	16.0	8.0	15	11.0	8.0
Nousak & Stapells, 1999				12	-2.5	6.6						

Note. *Difference score = ABR threshold (in dB nHL) minus pure-tone behavioural threshold (in dB HL).*

Table 4. Summary of Studies Reporting Tone-ABR Thresholds (in dB nHL) in Infants and Children With Sensorineural Hearing Loss as a Function of Frequency: Difference Scores (dB).

	500 Hz			1000 Hz			2000 Hz			4000 Hz		
Study	*n*	*M*	*SD*	*n*	*M*	*SD*	*n*	*M*	*SD*	*n*	*M*	*SD*
Hayes & Jerger, 1982	37	11.9	11.9				37	2.3	10.4			
J-I Suzuki et al., 1984	20	-1.3	7.8	20	-4.0	7.9						
Kileny & Magathan, 1987	14	-11.8	9.5									
Stapells et al., 1995	49	9.6	13.4				68	-0.2	12.0	30	-6.8	11.0
Balfour et al., 1998	5	-6.0	8.9	5	4.0	9.6	5	-2.0	9.8	5	-16.0	13.9
Aoyagi et al., 1999				93	6.8	14.1						

Note. *Difference score = ABR threshold (in dB nHL) minus pure-tone behavioural threshold (in dB HL).*

The 95% confidence intervals indicate a reasonably narrow range, about +/- 2 dB of the mean at each frequency.

The results for the infants and children with normal hearing are very similar to those for the adult participants. Measured in dB nHL, ABR thresholds for 500, 1000, and 2000 Hz tones are not different between infants/children and adults (based on overlap of the 95% confidence intervals). ABR 4000 Hz thresholds, however, are slightly higher (i.e., about 4 dB) for infants/children, with no overlap between the groups' confidence intervals at this frequency.

Overall, the results indicate ABR thresholds for participants with normal hearing are reasonably low (i.e., approximately 12 to 20 dB nHL) and quite consistent, with standard errors in the range of 0.5 to 0.9 dB.

The difference score results for the participants with sensorineural hearing loss are summarized in Table 6. For the adults with SNHL, ABR thresholds (in dB nHL) are, on average, 5.2 to 13.4 dB higher than their pure-tone behavioural thresholds (in dB HL). As with the results for adults with normal hearing, threshold estimation improves slightly from 500 to 4000 Hz; however, the 1000, 2000, and 4000 Hz confidence intervals overlap, indicating the small differences are not statistically significant. The 500 Hz confidence interval does not overlap with the 2000 and 4000 Hz results (indicating that they differ); the 500 and 1000 Hz confidence intervals overlap. The 95% confidence intervals indicate a reasonably narrow range, about +/- 3 dB of the mean at each frequency.

For the infants and young children with SNHL, their ABR thresholds are on average, 5.5 dB above (500 Hz) to 8.1 dB below (4000 Hz) their behavioural pure-tone thresholds. The 500, 1000 and 2000 Hz difference scores indicate a slight improvement with increasing stimulus frequency; confidence intervals suggest the 500 Hz results differ from those for 2000 Hz but not for 1000 Hz. The results indicate the 4000 Hz ABR thresholds of infants and young children with SNHL tend to underestimate their 4000 Hz pure-tone behavioural thresholds. It should be noted, however, that the number of pediatric participants for this frequency is quite low (only 35).

Except for the 4000 Hz results, the difference scores for the infants and young children with SNHL are smaller than those for adults with SNHL. The 95% confidence intervals indicate their 500, 1000, and 2000 Hz ABR thresholds (in dB nHL) are significantly closer to their pure-tone behavioural thresholds than are those of the adults. Without considering the direction of the difference (i.e., take the absolute value of the difference scores), their 4000 Hz difference scores are significantly worse compared to those of the adults. Possible explanations for these differences are considered in the discussion.

Considered overall, these results indicate the tone-evoked

Table 5. Summary of Mean Thresholds, Standard Errors, and 95% Confidence Intervals for Tone-ABR Thresholds (in dB nHL) in Participants With Normal Hearing as a Function of Frequency.				
	500 Hz	**1000 Hz**	**2000 Hz**	**4000 Hz**
Adults				
Mean Threshold (dB nHL)	20.4	16.2	13.4	11.8
Standard Error (dB)	0.8	0.6	0.5	0.5
95% Confidence Interval (dB nHL)	18.8 - 21.9	14.9 - 17.4	12.3 - 14.4	10.7 - 12.8
Number of Participants	271	271	216	258
Infants and Young Children				
Mean Threshold (dB nHL)	19.6	17.4	13.6	15.5
Standard Error (dB)	0.5	0.7	0.9	0.7
95% Confidence Interval (dB nHL)	18.8 - 20.5	16.0 - 18.7	11.8 - 15.5	14.1 - 16.8
Number of Participants	369	78	65	209

Table 6. Summary of Mean Difference Scores, Standard Errors, and 95% Confidence Intervals for Tone-ABR Estimation of Pure-Tone Behavioural Threshold in Participants With Sensorineural Hearing Loss as a Function of Frequency.				
	500 Hz	**1000 Hz**	**2000 Hz**	**4000 Hz**
Adults				
Mean Threshold (dB nHL)	+13.4	+10.3	+8.4	+5.2
Standard Error (dB)	1.2	0.9	1.0	1.4
95% Confidence Interval (dB nHL)	11.0 - 15.8	8.4 - 12.1	6.3 - 10.3	2.4 - 8.0
Number of Participants	85	167	100	84
Infants and Young Children				
Mean Threshold (dB nHL)	+5.5	+4.9	+0.6	-8.1
Standard Error (dB)	1.3	1.3	1.1	2.0
95% Confidence Interval (dB nHL)	3.0 - 8.0	2.4 - 7.3	-1.6 - +2.7	-12.1 - -4.1
Number of Participants	125	118	110	35

Note. *Difference score = Tone-ABR threshold (in dB nHL) minus Pure-Tone Behavioural Threshold (in dB HL).*

ABR threshold (in dB nHL) estimates a participant's pure-tone behavioural threshold (in dB HL) with quite reasonable accuracy in participants with SNHL. On average, the ABR threshold is within 10 to 15 dB of the pure-tone threshold. More importantly, these thresholds are quite consistent across participants, with 95% confidence intervals within +/- 4 dB of the mean differences.

Discussion

Across the 32 studies included in this meta-analysis, the tone-evoked ABR demonstrated acceptably low thresholds in individuals with normal hearing (i.e., 12 to 20 dB nHL), as well as reasonably accurate estimates of the pure-tone behavioural thresholds in individuals with sensorineural hearing loss (i.e., within 0 to 13 dB of behavioural threshold). Although differences exist between results for adults and those of infants and young children, the estimates demonstrated low standard errors, and appear quite accurate for both populations. These findings support the recent upsurge in interest in the use of the tone-evoked ABR to estimate the audiogram, as well as guidelines recommending its use for audiometric follow-up of infants who have failed a newborn hearing screening (e.g., American Speech-Language-Hearing Association, 1991; Bamford, 1997; Gravel, 2000; Joint Committee on Infant Hearing, 2000; The Pediatric Working Group, 2000).

Normal thresholds for the ABR to 500 Hz brief tones are elevated compared to those for higher frequency stimuli. These thresholds, however, are only 5 to 10 dB greater than 2000 and 4000 Hz. Equally important, the 500 Hz standard error is quite low and close to that of the other frequencies, indicating these thresholds are quite consistent across a large number of normal participants. Similar findings are seen for 500 Hz results in participants with sensorineural hearing loss. Thus, contrary to popular myth, the ABR to 500 Hz brief tones *does* provide an acceptably accurate assessment of pure-tone behavioural threshold (similar to the ABR for higher stimulus frequencies).

The ABR thresholds (in dB nHL) of infants and young children with normal hearing are the same as those from adults. The one exception to this is their ABR threshold at 4000 Hz, which is slightly higher (by about 4 dB) than the adults'. The explanation for this small difference at 4000 Hz is not clear. Sininger and colleagues have reported that neonatal ABR thresholds, relative to adult behavioural threshold (i.e., dB nHL), do not differ from those of adults (Sininger, Abdala, & Cone-Wesson, 1997). The ear canal SPLs of the brief-tone stimuli, however, were different between adults and newborns, with 4000 Hz being 24 dB more intense in neonates, whereas 500 Hz is only about 3 dB more intense (Sininger et al., 1997). Thus, although thresholds in nHL are similar, neonates require a higher dB SPL to reach threshold. Sininger and colleagues' results were obtained for neonates and ER-2 insert earphones (Sininger et al., 1997); results of the studies in this meta-analysis were obtained from both insert and circumaural earphones, and from neonates, infants and young children. The greater SPL in the ear canal does not appear to be able to explain the difference found in the present study. As suggested by the Sininger et al. data, it is possible that infant ABR thresholds to 4000 Hz stimuli are inherently higher (Sininger et al., 1997). Why this might be is not clear, although clinical experience suggests infants' ABR to 4000 Hz tones are lower in amplitude compared to their 2000 and 500 Hz responses, even for higher level (i.e., 60 to 80 dB nHL) stimuli.

Compared to adults with SNHL, the ABR-behavioural difference scores in infants and young children with SNHL are lower, except at 4000 Hz. Such results could be taken to indicate that the ABR better estimates thresholds in infants and young children than adults. While there may be some truth to this suggestion, there are other, more likely, explanations. Studies of ABR thresholds in infants are typically only carried-out when they are sleeping, and thus electrically quiet; studies in adults often are carried-out when they are awake (and perhaps reading), and thus electrically noisier. This could explain better threshold estimation. However, this is not likely a major factor, as ABR thresholds in infants and young children with *normal* hearing are the same as those of adults.

Rather, the lower difference scores (ABR threshold minus behavioural threshold) for infants and children with SNHL likely reflect combinations of (a) inaccuracy associated with behavioural testing of young children, (b) delays between ABR threshold and eventual behavioural threshold determination, and (c) maturational differences in ear-canal acoustic properties. Behavioural thresholds from infants, typically obtained using visual reinforcement audiometry, tend to be elevated compared to adults (Schneider & Trehub, 1992). If ABR thresholds are similar to those of adults, then the ABR-behavioural threshold difference would be smaller. Additionally, ABR thresholds are typically obtained several months before behavioural audiograms are considered reliable (Stapells, Gravel, & Martin, 1995). If an existing hearing loss worsened in the meantime (typically termed a "progressive" hearing loss), this would tend to make behavioural thresholds closer to, and even higher than, the ABR thresholds obtained at an earlier age. It is also likely this "progression" might be greater for higher frequencies such as 4000 Hz, resulting in the 4000 Hz ABR threshold, on average, being lower than the follow-up behavioural threshold (see Table 6). Further complicating matters are changes in the resonant frequency of the ear canal as a consequence maturational growth (Bentler, 1989; Kruger, 1987). These changes result in differences in stimulus SPL at the eardrum, especially in the 4000 Hz region (Feigin, Kopun, Stelmachowicz, & Gorga, 1989; Sininger et al., 1997).

The results of this meta-analysis suggest that the frequency specificity of thresholds determined by the ABR to brief tones are not a major concern, as evidenced by the reasonably accurate estimation of behavioural pure-tone thresholds at 500, 1000, 2000 and 4000 Hz for the large variety of degrees and configurations of hearing loss of participants in the studies included in this analysis. Some studies have specifically assessed the effects of audiogram configuration, either by quantitative analysis of different groups or through presentation results for individual participants (e.g., Balfour, Pillion, & Gaskin, 1998; Beattie, Garcia, & Johnson, 1996; Conijn, Brocaar, & van Zanten, 1993; Hayes & Jerger, 1982; Munnerley, Greville, Purdy, & Keith, 1991; Picton et al., 1979; Purdy & Abbas, 1989; Stapells, 2000; Stapells et al., 1995), with most concluding that there is little difference in results for differing configurations. One of the exceptions, Hayes and Jerger (1982), reported errors in estimation of 500 Hz threshold increased as the 1000 to 500 Hz audiometric slope increased. Picton and colleagues reported under-estimations of behavioural threshold in steep losses as a result of responses originating from stimulation by the brief tones' splatter of acoustic energy to regions with better hearing sensitivity, and demonstrated better estimation when this splatter is masked by band-reject ("notched") masking noise (Picton et al., 1979). Subsequently, the use of notched noise masking for tone-evoked ABR threshold testing was recommended (Picton, Stapells, & Campbell, 1981; Stapells & Picton, 1981; Stapells, Picton, Pérez-Abalo, Read, & Smith, 1985).

In the present meta-analysis, a total of eight studies employed notched (or, for 500 Hz, high-pass) noise masking (Beattie et al., 1996; Kileny & Magathan, 1987; Munnerley et al., 1991; Picton et al., 1979; Purdy, Houghton, & Keith, 1989; Sininger et al., 1997; Stapells et al., 1995; Stapells, Picton, Durieux-Smith, Edwards, & Moran, 1990). Threshold estimation results for participants with SNHL in those studies employing notched noise masking do not differ substantially from the studies without masking; the largest difference is seen for 4000 Hz, where thresholds obtained in notched-noise are about 2.5 dB higher. Thus, for the large majority of hearing losses, notched noise masking is not required. Nevertheless, when a very steep hearing loss is present (i.e., slope > 40 to 50 dB per octave), ABR thresholds to non-masked brief tones may under-estimate thresholds (Picton et al., 1979; Purdy & Abbas, 1989; Stapells et al., 1985), and addition of the notched noise masking may improve the accuracy of the estimate (Picton et al., 1979; Stapells et al., 1985). Blackman-windowed brief tones have been suggested as an alternative to notched noise masking (Gorga, Beauchaine, Kaminski, & Bergman, 1992; Gorga & Thornton, 1980); existing data, however, indicate no difference in the frequency specificity of the

ABR to linear- versus Blackman-windowed brief tones (Oates & Stapells, 1997a; Oates & Stapells, 1997b; Purdy & Abbas, 1989).

One area for further research is the use of the tone-evoked ABR for the assessment of profound hearing loss. Using current equipment, the ABR to brief tones does not appear to be able to distinguish severe-profound hearing losses in the range of 85 to 95 dB HL from those in the more profound ranges of 100 to 120 dB HL, especially at 500 Hz. Simply stated, a "no response" for the ABR may occur with a hearing level of 85, 100, or 120 dB HL. Stapells et al. (1995) reported 23% of the ears with no ABR present to 100 dB nHL 500 Hz tones showed pure-tone behavioural thresholds of 90 dB HL or better; 14% showed behavioural thresholds of 80 dB HL or better. Results for 2000 and 4000 Hz are somewhat better: 6 to 8% with no ABR at maximum stimulus levels show behavioural thresholds of 90 dB HL or better while 6% and 0% showed HLs of 80 dB or better at 2000 and 4000 Hz, respectively (Stapells, 2000; Stapells et al., 1995). Click-evoked ABR thresholds show similar issues for assessment of profound hearing loss (Brookhouser, Gorga, & Kelley, 1990). The limitation of the ABR for evaluation of profound loss is largely due to the 25 to 35 dB ppe SPL calibration levels for 0 dB nHL, and the output limitations of earphones.

Further research is required to determine whether use of transducers capable of higher output could provide a solution. It has recently been suggested that the brainstem auditory steady-state responses, elicited by continuous sinusoidally amplitude-modulated tones (and thus with lower 0 dB nHL calibration levels), are able to differentiate the various ranges of profound hearing loss (Rance, Dowell, Rickards, Beer, & Clark, 1998). One must be concerned, however, of possible cochlear trauma resulting from presentation of such high-intensity (e.g., 120 to 130 dB SPL) continuous pure-tone stimuli for the durations required to obtain a relatively noise-free evoked potential recording (necessary to conclude "response absent", Stapells, 2000). Such trauma is less likely to occur from the short-duration tones used to elicit the transient ABR.

There are a number of disadvantages to results of a meta-analysis such as carried-out in the present study. Although results across a large number of participants and studies may better reflect the in-the-field performance of the tone-evoked ABR for estimation of threshold, they necessarily increase variability and may not reflect "optimal" results for the technique. Across studies, 0 dB nHL calibration values likely differed, parameters and interpretation for the ABR differed, transducers differed (most studies used TDH 39 or 49 supra-aural earphones; some used ER-3A inserts), degrees and configurations of hearing loss differed, and, in the studies of pediatric participants, ages of ABR testing as well as behavioural follow-up varied. In view of this, the threshold estimation results reported in Tables 5 and 6 are remarkably accurate.

A primary use of the tone-evoked ABR is to assist in the initial fitting of hearing instruments when reliable behavioural thresholds are either not available or are incomplete. For example, an infant identified in the newborn period as having a hearing loss might be evaluated for amplification at three to four months of age, when behavioural thresholds are unreliable (American Speech-Language-Hearing Association, 1991; Gravel, 2000). Using the Desired Sensation Level (DSL) prescriptive hearing aid fitting procedure (Seewald, Moodie, Sinclair, & Cornelisse, 1996), thresholds in dB HL are corrected to threshold in dB SPL, either by age-specific estimated real-ear-to-coupler differences (RECD) or, preferably, by actual measurement of the RECD for the infant's ear using an ear-canal probe microphone (Moodie, Seewald, & Sinclair, 1994; Moodie, Sinclair, Fisk, & Seewald, 2000). A dilemma, however, arises with use of the ABR thresholds to predict the real-ear SPL. One might use the ABR-predicted adult "HL" values and correct them using the age-specific estimated or measured RECD. Alternatively, one might determine the coupler dB SPL values at threshold for the ABR, and then correct them using the age-specific estimated or measured RECD. A problem with this latter method is that thresholds (in dB SPL) for the brief-tone stimuli used to elicit the ABR are necessarily higher than those for long-duration pure-tone stimuli. For example: insert earphone 0 dB nHL for a brief 500 Hz tone is about 22 dB SPL (Stapells, 2000); insert earphone 0 dB HL for a long-duration 500 Hz tone is 5.5 dB SPL (American National Standards Institute, 1996). After the RECD correction, one would thus correct the obtained brief-tone threshold SPL to a more appropriate long-duration pure-tone SPL using the nHL-HL SPL differences. Finally, because clinical ABR thresholds are typically higher than the lowest possible ABR thresholds (due to collection of fewer trials in typical clinical protocols), and because ABR thresholds are usually 5 to 15 dB higher than behavioural thresholds for the same stimuli (Elberling & Don, 1987; Stapells et al., 1990), an "ABR-to-behaviour" correction factor is also required. Although the results of this meta-analysis clearly indicate that the ABR threshold (in dB nHL) to brief tones may be used to estimate with reasonable accuracy the pure-tone behavioural threshold (in dB HL), there are likely to be further refinements to improve its use for fitting of hearing instruments for infants.

In conclusion, this meta-analysis of the literature indicates tone-evoked ABR thresholds in individuals with normal hearing are typically 10 to 20 dB nHL. Tone-ABR thresholds in participants with SNHL are typically 5 to 15 dB higher than pure-tone behavioural thresholds in adult participants and from 10 dB lower to 10 dB higher than pure-tone behavioural thresholds in infants and young children. Importantly, threshold results are quite consistent across studies, with 95% confidence intervals no larger than ±5 dB. Unfortunately, these findings are not reflected in current audiological practice: although current guidelines recommend the use of tone-evoked ABR thresholds to guide the initial fitting of amplification in infants aged under six months (American Speech-Language-Hearing Association, 1991; Joint Committee on Infant Hearing. (2000; The Pediatric Working Group, 2000), recent surveys indicate, both in Canada and the United States, that only a minority of audiology centres who indicate a specialty in pediatric audiology routinely obtain ABR thresholds to tonal stimuli (Arehart, Yoshinaga-Itano, Thompson, Gabbard, & Brown, 1998; Brown, 2000). Clinicians must begin to use the tone-evoked ABR, and audiology training programs and workshops must ensure the training and experience is provided to their students and professionals to enable this important change.

Author Notes

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APPENDIX

Examples of studies excluded from the meta-analysis

1. Davis & Hirsh (1979): This classic paper is a summary of clinical experience of Davis and colleagues with the tone-evoked ABR. It concluded that "...brain stem electric responses allow us to estimate peripheral auditory thresholds at 500, 1000, 2000 and 4000 Hz with an accuracy of about ±10 dB" (Davis & Hirsh, p. 458). This study was excluded because it did not provide any group data (i.e., means and standard deviations could not be determined).

2. Hawes & Greenberg (1981): This paper shows ABR thresholds (V-"SN_{10}") of approximately 20 to 40 dB nHL for adults and newborns. It concluded that the slow brainstem response is a reliable indicator of hearing for 1000 Hz and above, and, with stimulus and recording parameter modifications, possibly at 500 Hz (Hawes & Greenberg). This study was excluded because it did not provide appropriate group data (i.e., means and standard deviations could not be determined were unavailable).

3. Laukli, Fjermedal, & Mair (1988): This paper assessed ABR thresholds to 500, 1000, and 2000 Hz tones in 35 children for whom behavioural audiometry was "not practicable". Recordings were obtained under anaesthesia in an operating room (ambient noise 56 dB SPL[A]). Many had just undergone myringotomies. ABRs were the average of ipsilateral and contralateral recording channels. The paper concludes that 500 Hz ABR thresholds are not reliable (Laukli, et al.). This study was excluded for a number of reasons: (a) it did not provide any group data — means and standard deviations could not be determined; (b) high ambient noise levels; and (c) summation of ipsilateral and contralateral recording channels.