ORIGINAL ARTICLE

# Effects of Age and Degree of Hearing Loss on the Agreement and Correlation Between Sound Field Audiometric Thresholds and Tone Burst Auditory Brainstem Response Thresholds in Infants and Young Children

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**Background/Purpose:** Early hearing rehabilitation programs eventually require measurement of the hearing threshold cutoff values over the whole range of speech frequencies. With tone burst auditory brainstem responses, excellent agreement and correlation between evoked-potential and behavioral thresholds have been demonstrated by previous studies. This study investigated the effects of different ages and degrees of hearing loss on the agreement and correlation in a large series of infants and young children in Taiwan.

**Methods:** Medical records were reviewed from a large series of 1281 infants and young children aged from 3 months to 3 years who had undergone diagnostic audiometry, including sound field audiometry and tone burst auditory brainstem response measurements. The effects of age and hearing loss on the agreement and correlation between two measured thresholds were studied.

**Results:** Significant correlations ($p < 0.001$) were seen between the two measured thresholds across groups of different ages and different degrees of hearing loss greater than 20 dB HL. However, the degree of correlation deteriorated at lower degrees of hearing loss. Correlations for hearing thresholds less than 20 dB HL were not significant at 1000, 2000 and 4000 Hz.

**Conclusion:** The evoked-potentials test, properly obtained and interpreted with respect to the effects of age and degree of hearing loss, may provide a very informative hearing threshold reference to help in behavioral audiometric evaluation in infants and young children with hearing loss. [*J Formos Med Assoc* 2008;107(11):869–875]

**Key Words:** auditory brainstem response, hearing loss, infant, pure-tone thresholds

With the advent of universal newborn hearing screening, infants and young children with potential hearing impairment undergo further hearing evaluation by measurement of auditory evoked potentials. Measurements of the auditory brainstem response (ABR) and auditory steady-state response are among the choices for evaluation of hearing. Although issues about safe sedation and increased costs are of concern, the evoked-potential results would objectively provide much detail on the degree and configuration of the hearing loss. Once hearing impairment is diagnosed clinically,



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provision of an early rehabilitation program requires assessment of the hearing thresholds over the whole range of speech frequencies. Though some infants and young children might not be able to complete the behavioral tasks necessary to provide accurate estimates of behavioral thresholds, any available behavioral pure-tone thresholds between 500 and 4000 Hz are very important information for use of the appropriate hearing devices.

Clinically, physicians and audiologists are therefore concerned about how well the evoked-potential measurements correlate with the behavioral audiological thresholds. Traditional click-evoked ABR (cABR) thresholds have been shown to correlate with behavioral thresholds in the 2000–4000 Hz range, but were not a reliable estimate of the low-frequency behavioral thresholds.[1,2] Later, with the clinical application of tone burst ABR (tABR) measurement, a high correlation between evoked-potentials and behavioral thresholds has been demonstrated across different frequencies by numerous authors.[3–8] The correlation and agreement at low frequencies may not be as high as those at high frequencies.[7] Generally, the reported average difference between behavioral and tABR thresholds for mid-to-high frequencies is less than 10 dB. When the effects of age are considered, immature neural sensitivity may affect the enhancement of auditory evoked potentials during infancy and childhood such that the thresholds tend to be elevated.[9,10] As for behavioral audiometry, the measurements are susceptible to the effects of arousal and attentiveness, which also relate greatly to age and individual development.[11,12] As regards hearing loss, the evoked-potential measurements are known to overestimate normal hearing and underestimate hearing loss in adults.[13,14] Accordingly, the correlation between tABR and behavioral thresholds is therefore affected by the chronological age and degree of hearing loss.

As the agreement and correlation between tABR and behavioral thresholds is generally reported to be good, we conducted this study to investigate the effects of age and degree of hearing loss on this association in a large series of infants and young children in Taiwan who underwent both hearing tests. To examine the effects of age and hearing loss, the agreement and correlation between thresholds measured by each method at four selected frequencies was determined and compared among groups of different ages and degrees of hearing loss. In addition to comparing our results with results from other studies, we also hoped to provide information for the establishment of protocols for measuring pure-tone hearing thresholds across speech frequencies in infants and young children.

## Methods

### *Subjects*

From 2000 to 2007, 1281 infants and young children aged from 3 months to 3 years were included as they had undergone diagnostic audiometry including sound field audiometry (SFA) and tABR measurements. All subjects had normal appearance of the external ears and eardrums as examined by qualified otolaryngologists. A-type tympanograms with 226 Hz probe tone were all acquired by a GSI 33 Middle Ear Analyzer (Grason-Stadler Inc., Milford, NH, USA). In the following process, SFA always preceded the tABR measurement to avoid potential bias from already known evoked-potential thresholds.

### *Procedure of SFA recording*

These measurements were performed using test procedures appropriate to the developmental level of the subjects (i.e. behavioral observation audiometry and visual reinforcement audiometry) in a test booth with audiometers calibrated to ANSI standards (S3.2, 1996).[15,16]

### *Procedure of tABR recording*

Testing was performed in a quiet room using the Bravo AEP system (Nicolet, Madison, WI, USA). Subjects were tested in a sedated stable physiologic state using chloral hydrate (50 mg/kg). The sequence of the ABR measurements was click, tone burst 500, 1000, 2000 and 4000 Hz in order as time permitted. Parameters of stimuli and recording settings were as described in our previous study.[17] In cases without sufficient sedation to go through the whole procedure, measurements would shift to the next frequency once the ongoing measurement reached 25 dB nHL to obtain the threshold measurements at all test frequencies. Therefore some 25 dB nHL thresholds obtained by the tABR test might suggest potentially better-than-25 dB nHL hearing thresholds.

### *Statistical analysis*

This study was conducted retrospectively on the basis of pre-existing records in an ordinary clinical setting. In addition, tABR threshold measurements tended to be affected by subject state and background noise level. Therefore, not every one of the recruited 1281 subjects had completed all the SFA or tABR threshold measurements. All available recordings at any test frequency were included in this study. Those values of SFA and tABR thresholds recorded as greater than the maximum output of the measuring apparatus were adopted as the numeric maximum for statistical analysis. The tABR threshold was defined by the tABR threshold measured in the better hearing ear for a given frequency. We evaluated the absolute difference and the correlation between SFA and tABR threshold values at matched frequencies (500, 1000, 2000 and 4000 Hz). Because the measured thresholds and the differences in threshold values were sparse and not of normal distribution, the variables were expressed by median and interquartile range (IQR), which is a measure of variability. Because the values of SFA and tABR thresholds were measured from the same subject, we used the nonparametric Wilcoxon signed-rank test to compare the differences between these two measurements. The Spearman rank-order correlation was applied to evaluate the association between the SFA and tABR thresholds across various stimulation frequencies. A two-tailed alpha level of 0.05 was considered statistically significant for all analyses. All the analyses were carried out using SAS version 9.0 (SAS Inc., Cary, NC, USA).

## Results

There were 1281 subjects (426 girls, 854 boys; mean age, 19.2 ± 10.0 months) recruited into this study. The distribution, differences and correlation coefficients between SFA thresholds and tABR thresholds at each test frequency are summarized in Table 1. Although the median differences between SFA and tABR threshold at all four selected frequencies were less than 10 dB, the differences in the absolute values between SFA and tABR thresholds reached statistical significance at three of the four frequencies (1000, 2000 and 4000 Hz, Table 1). In contrast, significant correlations between SFA and tABR thresholds were found at all of the four test frequencies ($p < 0.001$).

To investigate the roles of age on the agreement and correlation between SFA and tABR thresholds, we evaluated the absolute differences and the strength of correlation between the SFA and tABR thresholds stratified by age. Table 2 presents the absolute differences, correlation coefficients, $R^2$ (coefficient of determination), and

**Table 1.** Distribution, difference and correlation between sound field audiometry (SFA) thresholds and tone burst auditory brainstem response (tABR) thresholds at each test frequency

| Frequency | SFA (1) | | tABR (2) | | Difference* (1) – (2) | | | Correlation coefficient† (*p*) |
|---|---|---|---|---|---|---|---|---|
| | Median | IQR | Median | IQR | Median | IQR | *p* | |
| 500 Hz | 25 (1281) | 25 | 25 (558) | 25 | 0 (558) | 15 | 0.491 | 0.629 (< 0.001) |
| 1000 Hz | 25 (1274) | 25 | 25 (423) | 30 | 0 (422) | 15 | 0.009 | 0.678 (< 0.001) |
| 2000 Hz | 25 (1261) | 25 | 25 (353) | 40 | 5 (352) | 15 | < 0.001 | 0.737 (< 0.001) |
| 4000 Hz | 25 (1204) | 25 | 25 (326) | 40 | 5 (320) | 15 | < 0.001 | 0.698 (< 0.001) |

**Wilcoxon signed-rank test; †Spearman rank-order correlation. IQR = interquartile range.*

**Table 2.** Correlation between sound field audiometry (SFA) thresholds and tone burst auditory brainstem response (tABR) thresholds grouped by age

| Age (mo) | *n* | Frequency (Hz) | Difference* (SFA – tABR) | | | Correlation† | | |
|---|---|---|---|---|---|---|---|---|
| | | | Median | IQR | *p* | Correlation coefficient | $R^2$ | *p* |
| 3–6 | 108 | 500 | 0 | 15 | 0.150 | 0.598 | 0.358 | < 0.001 |
| | 83 | 1000 | 5 | 15 | 0.016 | 0.522 | 0.272 | < 0.001 |
| | 72 | 2000 | 5 | 15 | 0.015 | 0.595 | 0.354 | < 0.001 |
| | 68 | 4000 | 5 | 25 | 0.001 | 0.641 | 0.411 | < 0.001 |
| 7–12 | 95 | 500 | 0 | 15 | 0.219 | 0.638 | 0.407 | < 0.001 |
| | 83 | 1000 | 0 | 10 | 0.618 | 0.709 | 0.503 | < 0.001 |
| | 70 | 2000 | 5 | 20 | 0.002 | 0.754 | 0.569 | < 0.001 |
| | 67 | 4000 | 5 | 20 | 0.025 | 0.681 | 0.464 | < 0.001 |
| 13–18 | 75 | 500 | 0 | 20 | 0.802 | 0.600 | 0.360 | < 0.001 |
| | 56 | 1000 | 0 | 15 | 0.373 | 0.670 | 0.449 | < 0.001 |
| | 54 | 2000 | 5 | 15 | < 0.001 | 0.716 | 0.512 | < 0.001 |
| | 45 | 4000 | 5 | 15 | < 0.001 | 0.671 | 0.450 | < 0.001 |
| 19–24 | 89 | 500 | –5 | 15 | 0.015 | 0.665 | 0.443 | < 0.001 |
| | 65 | 1000 | 0 | 10 | 0.698 | 0.644 | 0.415 | < 0.001 |
| | 51 | 2000 | 5 | 10 | 0.004 | 0.842 | 0.709 | < 0.001 |
| | 48 | 4000 | 5 | 15 | 0.007 | 0.772 | 0.596 | < 0.001 |
| 25–30 | 124 | 500 | 0 | 10 | 0.123 | 0.438 | 0.192 | < 0.001 |
| | 90 | 1000 | 0 | 15 | 0.067 | 0.503 | 0.253 | < 0.001 |
| | 70 | 2000 | 5 | 10 | < 0.001 | 0.649 | 0.421 | < 0.001 |
| | 66 | 4000 | 5 | 15 | < 0.001 | 0.533 | 0.284 | < 0.001 |
| 31–36 | 67 | 500 | 0 | 20 | 0.353 | 0.575 | 0.330 | < 0.001 |
| | 45 | 1000 | 0 | 15 | 0.573 | 0.782 | 0.612 | < 0.001 |
| | 35 | 2000 | 5 | 15 | 0.099 | 0.710 | 0.504 | < 0.001 |
| | 26 | 4000 | 5 | 15 | 0.021 | 0.767 | 0.589 | < 0.001 |

**Wilcoxon signed-rank test; †Spearman rank-order correlation. IQR = interquartile range.*

the corresponding *p* values for the comparison between SFA and tABR thresholds in various age groups. The differences were generally not clinically marked because most of these median differences were less than the smallest recording scale (5 dB). Nevertheless, most of the absolute differences between SFA and tABR thresholds were statistically significant at 2000 and 4000 Hz (Table 2). The correlations were statistically significant at all tested frequencies of the different age groups ($p < 0.001$). In addition, the $R^2$ values of different age groups were similar without an obvious increasing or decreasing trend with age (Table 2).

Table 3 shows the difference and correlation between SFA and tABR thresholds stratified by the degree of hearing loss. The $R^2$ values tended to decrease with a lower degree of hearing loss. Children with a hearing threshold greater than 40 dB presented with the highest correlation between the two thresholds at all tested frequencies ($R^2$ range, 0.537–0.643), which was followed by the children with hearing threshold in the 20–40 dB range ($R^2$ range, 0.059–0.109), and the children with a less than 20 dB hearing threshold showed the least correlation ($R^2$ range, 0.001–0.034), with insignificant correlation at 1000, 2000 and 4000 Hz ($p > 0.05$).

**Table 3.** Correlation between sound field audiometry (SFA) thresholds and tone burst auditory brainstem response (tABR) thresholds grouped by degree of hearing loss

| SFA threshold | *n* | Frequency (Hz) | Difference* (SFA – tABR) | | | Correlation† | | |
|---|---|---|---|---|---|---|---|---|
| | | | Median | IQR | *p* | Correlation coefficient | $R^2$ | *p* |
| < 20 dB | 153 | 500 | 0 | 20 | < 0.001 | 0.184 | 0.034 | 0.023 |
| | 100 | 1000 | 0 | 15 | 0.018 | 0.174 | 0.030 | 0.083 |
| | 83 | 2000 | 0 | 10 | 0.035 | 0.089 | 0.008 | 0.423 |
| | 87 | 4000 | 5 | 15 | 0.003 | 0.008 | 0.001 | 0.938 |
| 20–40 dB | 270 | 500 | 5 | 15 | 0.006 | 0.244 | 0.059 | < 0.001 |
| | 203 | 1000 | 5 | 15 | < 0.001 | 0.271 | 0.074 | < 0.001 |
| | 157 | 2000 | 5 | 15 | < 0.001 | 0.330 | 0.109 | < 0.001 |
| | 142 | 4000 | 10 | 15 | < 0.001 | 0.280 | 0.079 | < 0.001 |
| > 40 dB | 135 | 500 | –5 | 10 | 0.525 | 0.733 | 0.537 | < 0.001 |
| | 119 | 1000 | 0 | 10 | 0.374 | 0.769 | 0.592 | < 0.001 |
| | 112 | 2000 | 5 | 15 | < 0.001 | 0.802 | 0.643 | < 0.001 |
| | 91 | 4000 | 5 | 15 | < 0.001 | 0.787 | 0.620 | < 0.001 |

**Wilcoxon signed-rank test; †Spearman rank-order correlation. IQR = interquartile range.*

## Discussion

Most of the literature studying correlations of thresholds between evoked potentials and behavioral audiometry have included adults with low sample numbers.[1,2,4–8] In contrast, the present study focused on subjects aged less than 3 years of age and included a large population of 1281 subjects over 8 years. With the more focused group and larger population, the purpose of this study was to investigate how the agreement and correlation of thresholds estimated by SFA and tABR tests were affected by age and hearing loss in infants and young children. To summarize, similar agreement and correlation were noted for subjects aged from 3 to 36 months (Table 2), which suggests that the effects of age are not marked. As for the effects of degree of hearing loss, paradoxically the correlation strength deteriorated along with decreased degree of hearing loss (Table 3), which will be discussed below. In addition, correlations at lower frequencies were comparable to those at higher frequencies, which is different from a previous report.[7]

According to previous studies, the strongest correlations between cABR thresholds and pure-tone thresholds were observed at 2000 and 4000 Hz.[1,2] The frequency-specific correlation was related to the characteristic of click as an impulsive stimulus and the nature of the cochlear frequency map.[8,18] Later tABR, having stimuli with rapid onset, short duration, and centered energy at the nominal frequency, could effectively elicit responses giving information across frequencies. It is thus of interest to know whether the correlation between tABR thresholds and pure-tone behavioral thresholds is frequency specific or not. Several studies have described the comparison between tABR thresholds and audiometric pure-tone thresholds in populations including adults. They generally indicate frequency-specific agreement and correlation between the two threshold measures, but some suggest the associations decline at lower frequencies.[3–8] The results of this study also demonstrated good agreement and correlation across four selected audiometric frequencies in infants and young children. The median differences at four frequencies were all less than 10 dB, although significant differences were noted at 1000, 2000 and 4000 Hz (Table 1). The correlation coefficients were satisfactory with statistically significant *p* values ($p < 0.001$, Table 1). Correlations at lower frequencies were comparable to those at higher frequencies.

Regarding the effects of age on the agreement and correlation between the two measurements, the reasons for recruiting subjects older than 3 months were that our audiologists felt more comfortable with the results of SFA when the infant was older than 3 months of age. As shown in Table 2, subjects of all age groups showed similar and significant correlations between SFA and tABR measurements, which suggests that behavioral audiometry is reliable for subjects older than 3 months of age. In addition, the $R^2$ values between SFA and tABR appeared to be satisfactory for children of different age groups from 3 month to 3 years (Table 2).

As for the effects of various degrees of hearing loss on the agreement and correlation between the two measurements, the agreement did not change while the strength of correlation paradoxically deteriorated along with a decreased degree of hearing loss. Clinically, the tABR procedures are often performed when young children need sedatives to enter a condition for accurate tABR measurement. However, there is no guarantee that young children will sleep long enough to complete the measurements at each test frequency. After further investigation of the performance of tABR measurements retrospectively, we have learned that our audiologists may have bypassed the measurements at stimuli lower than 25 dB nHL at any test frequency and shifted to the next test frequency because of concern at the limited time to complete all measurements at all frequencies. Pragmatically, it was assumed that the subject may have normal hearing at lower frequencies to pass the tABR test at 25 dB nHL. The above manipulation would not happen when performing the SFA as time was not as limited as it was for tABR measurements. This may explain why the correlation strength between the two thresholds became weak with nonsignificant $p$ values ($p > 0.05$) at 1000, 2000 and 4000 Hz for those with less than 20 dB HL hearing loss. In addition, because of the limited time and the sequence from low to high frequencies in performing tABR measurements, incomplete measurements were mostly at high frequencies. These incomplete measurements gave an explanation for the greater median differences at 2000 and 4000 Hz for most groups stratified by age or hearing loss even though there were still significant correlations (Tables 2 and 3).

To perform evoked-potential measurements for young children, safe sedation is deemed important and necessary, which requires on-site medical staff, monitoring equipment, and additional precautions. These factors result in increased costs and longer test times. To speed up the measurements, as the cABRs are typically the easiest to measure and collected quickly while providing guidance for subsequent stimuli, the paradigm of ABR threshold measurement in this study always started from click stimuli and proceeded to tone burst stimuli at low frequency, then at mid frequency, and, if time permitted, at high frequency. To collect the most important information in the least amount of time, we recommend the above ABR measurement procedures for hearing evaluation in infants and young children.

Incomplete evaluation of hearing loss at any audiometric speech frequency may often cause difficulties for the initial fitting of hearing devices if the degree and configuration of hearing loss is not flat and smooth. Information on tABR thresholds at those frequencies accordingly facilitate and complete the accurate measurement of behavioral audiological thresholds. In another aspect, the good agreement and correlation between two thresholds suggest that the tABR thresholds alone may have sufficient accuracy to initiate a program of rehabilitation for patients who are unable to provide reliable behavioral responses to sound stimuli.[8] However, it also reminds us that the tABR threshold is not always an exact hearing threshold at speech frequencies. Behavioral testing should always be conducted when the child is developmentally ready. The evoked-potentials test, properly obtained and interpreted with respect to the effects of age and degree of hearing loss, may provide a very informative hearing threshold reference to perfect the behavioral audiometric evaluation in infants and young children with hearing loss.

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