Auditory Brainstem Response Wave I Prediction of Conductive Component in Infants and Young Children

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Wave I latencies were used to predict the magnitude of conductive components in 80 infants and young children (122 ears) with normal hearing, conductive hearing loss due to otitis media or aural atresia, sensorineural hearing loss, and mixed hearing loss. Two prediction methods were used. The first method based predictions on a 0.03-ms wave I latency delay for each decibel of conductive hearing loss. The second method was based on a regression analysis of wave I latency delays and the magnitude of conductive component for the subjects in this study with normal cochlear status. On average, these prediction methods resulted in prediction errors of 15 dB or greater in over one-third of the ears with hearing loss. Therefore, the clinical use of wave I latencies to predict the presence or magnitude of conductive impairment is not recommended for infants and young children. Instead, bone-conduction ABR testing is recommended as a direct measure of cochlear status when behavioral evaluation is not possible.

Audiologists involved in the assessment of hearing in infants and difficult-to-test patients are often unable to obtain reliable behavioral information regarding hearing sensitivity. In such instances, auditory brainstem response (ABR) testing is used to obtain further information. As in any hearing evaluation, when a hearing loss is identified through ABR testing, it is important to estimate the degree of cochlear involvement. In behavioral testing, this is normally accomplished through bone-conduction testing; however, bone-conduction ABR testing is not routinely done in the clinic.

Latency measures obtained from the ABR to air-conducted stimuli provide a potential source of information not available from the behavioral air-conduction audiogram. Latencies increase as stimulus intensity decreases (for review, see Hall, 1992, pp. 126–133), and conductive hearing loss reduces the effective intensity arriving at the cochlea. Consequently, ABR latencies are often prolonged in cases of conductive hearing loss. It is a commonly held belief that these ABR latency shifts can be used to predict the extent of conductive involvement with reasonable accuracy.

The relationship between ABR latency and the magnitude of conductive loss has been examined for both wave I (Berlin & Gondra, 1976; Chisin, Gafni, & Sohmer, 1983; Conijn, van der Drift, Brocaar, & van Zanten, 1989; Eggermont, 1976; Fria & Sabo, 1979; Mendelson, Salamy, Lenoir, & McKean, 1979; Salomon & Elberling, 1988) and wave V (Borg, Lofqvist, & Rosén, 1984; Chisin et al., 1983; Conijn et al., 1989; Fria & Sabo, 1979; McGee & Clemis, 1982; van der Drift, Brocaar, & van Zanten, 1988; van der Drift, van Zanten, & Brocaar, 1989; Yamada, Yagi, Yamane, & Suzuki, 1975). There are at least two methods that have been used to predict conductive hearing loss using wave I and wave V latency delays. One method is based on the horizontal shift from the normal wave I or V latency-intensity (LI) function. For example, Yamada et al. (1975) extended a horizontal line from the latency value at normal threshold (10 dB for their subjects) to the point of intersection with the subject’s LI function, and then calculated the difference (in dB) between the normal threshold and the intensity at the point of intersection. A second method, using wave I latency, estimates the magnitude of the conductive component from the latency delay at a single intensity, where each 0.3-ms delay from the mean of normal latency values corresponds to 10 dB of conductive loss (Fria & Sabo, 1979).

Results from these studies have been mixed. Predictions for ears with known conductive hearing loss have been reasonably good. For example, van der Drift et al. (1989) reported that predictions of magnitude of conductive loss...
based on wave V latencies were within 16 dB in 95% of the conductive hearing losses examined. Yamada and coworkers reported that predictions based on wave V latencies were within 15 dB in 83% of their cases (Yamada et al., 1975). McGee and Clemis (1982) reported that predictions were generally within 10 dB for ears with otitis media (OM) or artificially induced (i.e., occluded) hearing loss; however, there was a tendency to overestimate the magnitude of conductive loss in ears with ossicular chain disorders.

When studies included subjects with sensorineural or mixed hearing losses, results were not as favorable. This is closer to the clinical situation in which the type of hearing loss would not be known at the time of testing. The data of van der Drift and his colleagues show overlap between categories of conductive and cochlear hearing loss for ABR thresholds of 40 dB nHL and less (van der Drift et al., 1988). These investigators subsequently reported that they were unable to differentiate between cochlear and mixed hearing loss (van der Drift et al., 1989). Chisin et al. (1983) examined the relationship between wave I and V latencies and hearing loss in ears with conductive, sensorineural, and mixed losses. Moderate correlations were reported between the air-bone gap (average at 0.5, 1, and 2 kHz) and waves I and V latencies; however, their best correlation for this relationship (.59 for mixed losses, using wave I) accounts for only 35% of the variance. In addition, these correlation coefficients were not significant for sensorineural hearing losses using wave I or for mixed hearing losses using wave V, suggesting that in the presence of reduced cochlear sensitivity, the relationship between the magnitude of conductive component and latency delay is even weaker.

Several studies have compared wave V versus wave I latencies for prediction of conductive loss (Chisin et al., 1983; Conijn et al., 1989; Fria & Sabo, 1979). Conijn et al. (1989) reported that correlations between latency and conductive loss were similar for waves I and V. In contrast, Chisin et al. (1983) showed that correlation coefficients based on wave I latencies were slightly better in the majority of cases. Fria and Sabo (1979) compared predictions based on wave V latency and wave I latency delays in school-aged children who had indications or history of otitis media (OM). The magnitude of conductive impairment was estimated from wave V latencies using the technique described by Yamada et al. (1975), whereas for wave I latencies, predictions were based on a 0.3-ms delay equalling 10 dB of conductive loss. Fria and Sabo (1979) reported a 20-dB error in prediction for 20% of the cases using wave I latency delays, and for 10% of the cases using wave V latency delays.

Waves I and V latency delays have also been used to predict the presence of otitis media in younger subjects for whom audiometric information was unavailable. Fria and Sabo (1979) used waves I and V latency delays to evaluate the sensitivity for detection of OM in 12 infants and toddlers ranging in age from 4 to 39 months. Sensitivity was good for both measures (wave I—82%; wave V—100%); however, the specificity was much poorer using wave V latencies (wave I—100%; wave V—25%), with a tendency for wave V to overpredict the presence of otitis media. The poor specificity using wave V latencies was attributed to age-related variability and maturational changes associated with wave V latency. Mendelson et al. (1979) also reported that wave I delays were superior to wave V in predicting the presence of otitis media. Given the findings of Mendelson et al. (1979) and Fria and Sabo (1979), it is generally believed that wave I latency is more appropriate than wave V latency for predictions of conductive loss in infants and young children.

In addition to the disparities between studies described above, there are still unresolved issues that must be addressed before applying a predictive technique in a clinical setting. First, techniques predicting the magnitude of conductive component would be applied primarily to infants, yet the studies cited above examined only a few infants. This was presumably because of the difficulty in obtaining a measure of cochlear sensitivity in infants, and thus in estimating the actual conductive component. Those studies that included infants did not differentiate the results of infants and older subjects. Second, conductive component predictions need to be accurate for patients with all types of hearing loss; thus, further study of these predictions is needed in infants with conductive, sensorineural, and mixed losses.

The purpose of the present study was to extend the work of Fria and Sabo (1979) to include infants and young children with otitis media, aural atresia, mixed hearing loss, and sensorineural hearing loss. The predictions of conductive component were determined from wave I latency delays. Wave V latency delays were not considered in this paper due to the variability associated with brainstem maturation. Classification of cochlear status in ears with hearing loss was determined using brainstem responses to bone-conducted tones (Foxe & Stapells, 1993; Stapells, 1989; Stapells & Ruben, 1989).

Methods

Subjects

Clinic files were examined for 80 infants and young children (122 ears) seen for auditory brainstem response evaluations in the Auditory Evoked Potential Laboratories of the Albert Einstein College of Medicine. Subjects ranged in age from 2 weeks to 96 months, with a mean age of 22 months (standard deviation [SD] = 23 months), and a median age of 11.5 months. Data were categorized into the following categories of hearing loss: normal hearing, conductive hearing loss—otitis media, conductive hearing loss—otitis media, sensorineural hearing loss, and mixed hearing loss. The primary determinants for group placement were responses to air- and bone-conducted stimuli. Normal hearing ears (N = 13) were defined as those in which auditory brainstem responses were present to air-conducted 2,000-Hz tones or clicks presented at 20 dB nHL (Stapells, 1989; Stapells & Foxe, 1990; Stapells, Gravel, & Martin, 1993; Stapells, Picton, & Durieux-Smith, 1994). Ears with conductive hearing loss (N = 71) were those in which ABR thresholds to air-conducted clicks or 2,000-Hz tones were elevated (i.e., threshold 30 dB nHL or greater) with ABRs
to bone-conducted 2,000-Hz tones present at the normal screening intensity of 30 dB nHL. The differences in normal criteria for air- (20 dB nHL) and bone-conducted (30 dB nHL) stimuli reflect the differences of normal infants’ responses to air- and bone-conducted stimuli (Foxe & Stapells, 1993; Stapells & Ruben, 1989). Ears with conductive hearing loss were subdivided into otitis media (N = 55) and atresia (N = 16) categories according to etiology. Ears with sensorineural hearing loss (N = 35) were those in which ABR thresholds for air- and bone-conducted stimuli were both elevated, and bone-conduction thresholds were not more than 10 dB better than air-conduction thresholds. Ears with mixed hearing loss (N = 3) were those in which ABR thresholds for air- and bone-conducted stimuli were both elevated, and the bone-conduction thresholds were more than 10 dB better than the air-conduction thresholds.

In nine ears, bone-conduction ABR results were not available, and behavioral results were used to categorize the type of loss. In three of these ears, behavioral thresholds were used because ABR threshold information (air- or bone-conducted) was not available. There was a total of 28 ears for which both ABR and behavioral results were available, and behavioral thresholds confirmed the degree and category of hearing loss for all of these ears. In total, there was behavioral confirmation of hearing loss category and threshold for 37 ears. In the remaining 85 ears, behavioral audiometric results were inconclusive due to the developmental status of the child.

**ABR Recordings**

Two-channel recordings were obtained using gold-plated cup electrodes placed at the vertex (noninverting) and on each mastoid (inverting). A fourth electrode placed on the forehead served as ground. Interelectrode impedances were 3,000 Ω or less. The EEG was amplified and filtered (30–3,000 Hz, 12 dB/octave). Trials containing amplitudes exceeding ±25 μV were automatically rejected. The EEG was monitored on an oscilloscope throughout the test session, and testing proceeded only when subjects were asleep. Subjects aged less than 6 months were tested in natural sleep, and those aged 6 months and older were tested under chloral hydrate sedation prescribed by a physician.

Responses were recorded to high-intensity rarefaction clicks presented at a rate of either 19.1 (81% of ears) or 61.1 per second. An intensity of 80 dB nHL was used for the majority of subjects; however, intensities up to 100 dB nHL were used when necessary in order to obtain a clear and replicable wave I.

Responses to air-conducted clicks or 2,000-Hz tones were recorded at lower intensities either to establish normal hearing or to determine ABR thresholds. Threshold searches (10-dB steps) for air-conducted stimuli were conducted only for those ears not exhibiting responses at the normal air-conduction intensity of 20 dB nHL. Thresholds to 61.1 per second rarefaction clicks were obtained for eight ears. For the remaining 111 ears with ABR thresholds, 2,000-Hz (“2-1-2 cycle”) tones were presented at a rate of 39.1 per second (Stapells, 1989; Stapells & Foxe, 1990; Stapells et al., 1994). The use of different stimuli reflects a change in clinic protocols over the course of the data collection period.

Brainstem responses to bone-conducted 2,000-Hz tones were recorded either to determine bone-conduction ABR thresholds or to establish normal cochlear sensitivity. Stimuli were presented through a Radioear B70A oscillator placed on the temporal bone in a superoposterior auricular position and held in place with 350–450 grams of force. Threshold searches (10-dB steps) for bone-conducted stimuli were conducted only for ears with both elevated air-conduction thresholds and no response at the normal bone-conduction intensity of 30 dB nHL. The 30 dB nHL criterion for normal was used because all normal infants in previous studies showed responses at this intensity (Foxe & Stapells, 1993; Stapells & Ruben, 1989). Whenever masking was not used during bone-conduction ABR testing, ipsilateral/contralateral response asymmetries were used to determine ear-specific responses. Further details of our bone-conduction stimuli and technique for ABR testing are given in our recent papers (Foxe & Stapells, 1993; Nousak & Stapells, 1992; Stapells, 1989; Stapells & Ruben, 1989).

Testing was performed in a double-walled sound-attenuating room (IAC). A minimum of two replications of 2,000 trials each was obtained for each condition. Additional replications were obtained when necessary to confirm the presence of the response.

Tympanometry was performed on 92% of the ears (97/106, excluding the 16 atretic ears), with a 220-Hz probe tone used for subjects 6 months of age and older and a 660-Hz probe tone for subjects aged less than 6 months (ASHA, 1991; Marchant et al., 1986). Ipsilateral acoustic reflex testing was conducted whenever possible. In 95% of these ears, tympanometric findings were consistent with the hearing loss category, as were the physical findings for all 16 atretic ears.

**Data Analysis**

Wave I latency was measured for each subject’s data. Latency delays were calculated using the laboratories’ normative database, which was obtained from a larger group of normal subjects who are not included in this study. Latency delay was calculated by subtracting from each subject’s wave I latency the mean of the normative data for a given rate/intensity combination.

The magnitude of the conductive component was determined for each ear. Because bone-conduction threshold searches were not carried out for ears with conductive hearing loss, bone-conduction results were not used for the determination of the magnitude of conductive components. The exception to this was the mixed hearing loss group that included only three ears. For the conductive hearing loss categories (otitis media and atresia), the conductive component was calculated as the air-conduction threshold minus 10 dB, as ABR thresholds tend to overestimate the behavioral thresholds by approximately 10 dB (e.g., Elberling & Don, 1987; Kodera, Yamane, Yamada, & Suzuki, 1977; Picton, Stapells, & Campbell, 1981;
Suzuki, Kodera, & Yamada, 1984; Yamada et al., 1975). For the group with mixed hearing loss only, the difference between the air-conduction and bone-conduction ABR thresholds was used to estimate the magnitude of the conductive component. A conductive component of 0 dB was used for ears in the normal hearing and sensorineural hearing loss categories.

Linear regression analyses were carried out on the combined data for normal ears and those with conductive hearing loss, using wave I latency delay and the conductive component as the variables. The conductive component was then predicted for individual subjects using two methods. First, using the method proposed by Fria and Sabo (1979), the conductive component was derived by dividing the wave I latency delay by 0.03 ms (based on 0.3-ms latency delay per 10 dB of conductive hearing loss). Second, the conductive component was predicted using the regression equation from our data analysis.

**Results**

ABR air-conduction thresholds and corresponding wave I latency delays are plotted in Figure 1. Each point represents one ear. Average and standard deviation ABR thresholds were 43.5 ± 12.2 dB nHL for the ears with otitis media, 63.1 ± 10.1 dB nHL for the ears with atresia, 66.7 ± 15.3 dB nHL for the ears with mixed loss, and 50.4 ± 18.7 dB nHL for those with sensorineural hearing loss. All ears in the normal group had clear responses at 20 dB nHL and, therefore, thresholds less than or equal to this intensity. The average wave I latency delay for the normal-hearing group is 0.06 ms (SD = 0.2 ms), indicating no overall difference from our larger normative database. There is an overall trend for wave I latency to increase with increasing hearing loss; however, the range of latency delay is quite large for any specific threshold level. This is true even within specific hearing loss groups. Ears with sensorineural loss (open squares) tend to show smaller wave I delays; however, there are several with large delays. Of importance, there is considerable overlap of data between groups for a given magnitude of latency delay or for a given threshold. Note, for example, the overlap between latency delay for otitis media and sensorineural hearing loss for a 40 or 60 dB nHL threshold. Finally, the range of the normal ears’ latency delays overlaps that of conductive hearing losses having thresholds as great as 70 dB nHL.

All except one of the normal ears showed wave I latencies within our clinical norms (i.e., ±2.5 SD of the mean). The one exception showed a prolonged wave I latency of 1.98 ms (0.44 ms delay). Despite this delayed latency, this 7-month-old infant showed clear responses to 2000-Hz air-conducted tones at 20 dB nHL, with normal wave V latencies. The response to 80 dB nHL clicks (19.1 per second) showed normal waves III and V latencies. Further, acoustic immittance results were consistent with tympanic membrane mobility.

The linear regression carried out on the data for the normal ears and ears with conductive hearing loss resulted in the equation

\[ Y = 14.32026 + 25.67061 \times X \]

where X is the wave I latency delay (in ms), and Y is the magnitude of the conductive component (in dB). Although statistically significant, the correlation coefficient for these data indicates that the equation accounts for only 45% of the variance \((r = .67, df = 82, p < .001)\).

The magnitude of error in prediction (in dB) for each ear with hearing loss was determined using the prediction formula (0.03 ms/dB of conductive component) employed by Fria and Sabo (1979) and the resulting regression equation shown above. These results are shown in Table 1. Error was calculated using the conductive component minus the predicted conductive component. Negative numbers indicate that the prediction overpredicted the magnitude of the conductive component; positive numbers indicate underpredictions.

Wave I latency delays predicted conductive components in some normal ears because of the range of latencies observed in subjects with normal hearing. As shown in Table 1, the range of prediction “errors” (i.e., anything other than 0 dB) in normals is large, spanning a 22-dB range using the 0.03 ms/dB equation. The regression equation resulted in an average overprediction of 16 dB in the normal group, largely due to the 14.3-dB constant in the equation.

For all hearing loss, the average predicted conductive component was within 5 dB of the measured conductive component for both prediction methods, however, the range of errors was greater than 80 dB for both techniques. The worst predictions were found in ears with sensorineural components. This is because these prediction methods do not take into account wave I latency delays produced by cochlear hearing loss.

Figure 2 shows, for each group and prediction method, the percentage of ears in which the prediction error (i.e., the absolute value of the error) is equal to or exceeds 10, 15, 20, and 30 dB. Overall, the error in prediction for all
hearing losses was 15 dB or greater in 35% and 39% of the
ears for predictions determined using the 0.03 ms/dB
equation and regression equation, respectively. The
regression equation provided the best predictions of
conductive component for ears with conductive hearing
loss, but resulted in large errors in ears with sensorineural
components. In contrast, the 0.03 ms/dB equation resulted
in the smallest errors in prediction for the ears with
sensorineural hearing loss, with the largest prediction
errors for the conductive groups.

Discussion

The results of this study suggest that, at best, wave I latency delay accurately predicts (i.e., less than 15 dB
error) the magnitude of conductive involvement in only 61% to 65% of hearing losses. Thus, in approximately one
out of three cases, clinicians attempting to estimate the
magnitude of conductive component using wave I latency
delays are likely to err in their prediction by at least 15 dB.
In one out of every 12 patients, this error will be 30 dB or
greater.

Predictions were better for some categories of hearing
loss than others. Predictions were within 15 dB in 76% of
the ears with otitis media using the regression equation,
which is only slightly poorer than the 80% predictive
accuracy reported by Fria and Sabo (1979) for their 10
school-aged subjects. However, using the 0.03 ms/dB
equation recommended by Fria and Sabo (1979), only 55%
of the ears with otitis media in the present study were
within 15 dB.

Prediction of conductive components from air-
conduction ABR latency delays has several disadvantages.
First, the range of wave I latencies in normal ears is large
(1.41 to 1.98 ms for the 13 subjects with normal hearing in
this study), resulting in considerable overlap with some of
the hearing loss groups. Thus, as Eggermont has noted, the
minimum amount of conductive impairment that can be
detected is about 20 dB, and the inaccuracy of predictions
for conductive losses exceeding this amount is also about
20 dB (due to the 20-dB range in latencies seen for normal
between conductive, sensorineural, and mixed hearing
losses is complicated by the fact that wave I and V
latencies are often prolonged in cases of cochlear hearing
losses (e.g., Coats, 1978; Eggermont, 1982; Elberling,
1981). Wave V latencies are also often prolonged in
retrocochlear hearing losses (for review, see Hall, 1992).

Predictions based on wave I latency, however, have the
advantage of not being influenced by post-term matura-
tional changes (Schwartz, Pratt, & Schwartz, 1989) and
infrequently by retrocochlear pathology (Eggermont,
Predictions from previous studies that restricted analyses to subjects with known conductive hearing loss have been reasonably good. When evaluating infants in a clinical situation, however, one rarely knows the type of hearing loss prior to evaluation. In the case of an infant with otitis media, one may be tempted to rely on a combination of tympanometry and latency-based predictions to arrive at a diagnosis of conductive hearing loss. The danger of this approach is illustrated in the following example. One 6-month-old subject in this study presented with a flat tympanogram and elevated ABR air-conduction threshold (40 dB nHL). Based on a wave I latency delay of 0.82 ms, both equations would have predicted that the hearing loss was conductive, however a bone-conduction ABR threshold of 50 dB nHL was obtained, indicating a sensorineural hearing loss. Relying on the acoustic immittance results and air-conduction ABR predictions rather than a direct measure of cochlear sensitivity would have resulted in a misdiagnosis of the nature of the child’s hearing loss. This example underscores the importance of obtaining a direct measure of cochlear sensitivity by obtaining responses to bone-conducted stimuli. Otitis media often coexists with sensorineural hearing loss and does not always result in substantial air-bone gaps. Sensorineural hearing loss often results in prolonged latencies, further complicating these predictions.

Neither of the prediction methods accurately estimated the conductive components for all types of hearing loss. The regression equation gave better predictions for ears with conductive hearing loss, but showed large errors in ears with sensorineural components. The opposite pattern was found using the 0.03 ms/dB equation.

Because of the use of bone-conduction stimuli, the cochlear status of all the infants and children with impaired hearing in the present study was known, allowing for determination of appropriate therapeutic intervention. Further, armed with the bone-conduction information, it was possible to provide parents with more definitive information regarding their child’s hearing loss and recommended course of intervention.

Although not yet widely used by clinicians, there are very few difficulties in recording the ABR to bone-conducted stimuli. Care must be taken to ensure that the oscillator is adequately placed and the applied force is appropriate (Stuart, Yang, & Stenstrom, 1990; Yang & Stuart, 1990; Yang, Stuart, Stenstrom, & Hollett, 1991). There appear to be maturational differences in responsivity to bone-conducted stimuli such that these stimuli may be effectively more intense for neonates and young infants (Foxe & Stapells, 1993; Nousak & Stapells, 1992; Yang, Rupert, & Moushegian, 1987). Normal response levels are thus determined from infant response detectability rather than adult normal hearing levels (Stapells & Ruben, 1989). Masking of the contralateral ear during bone-conduction ABR testing may not be as critical as in adults because there appears to be greater interaural attenuation of bone-conducted stimuli in infants (Yang et al., 1987). Further, large ipsilateral/contralateral ABR asymmetries observed in infants may be used to determine the ear of response origin (Foxe & Stapells, 1993; Jahrsdoerfer, Yeakley, Hall, Robbins, & Gray, 1985; Stapells & Ruben, 1989). It should be noted that studies are in progress concerning the ABR to BC stimuli. In addition to the 28 ears in this study with both BC ABR and reliable behavioral audiograms, further studies of subjects with known audiograms are required to confirm the accuracy of the ABR to BC stimuli.

Recent studies (Foxe & Stapells, 1993; Gorga, Kaminski, Beauchaine, & Bergman, 1993; Kramer, 1992; Nousak & Stapells, 1992; Stapells & Ruben, 1989; Stuart et al., 1990; Yang & Stuart, 1990; Yang, Stuart, Mencher, Mencher, & Vincer, 1993; Yang et al., 1991) as well as current ASHA guidelines support the clinical use of auditory brainstem responses to bone-conducted stimuli. Specifically, the ASHA guidelines recommend that when “air-conducted ABR is elevated, an ABR to bone-conducted stimuli should be considered” (ASHA, 1991). Although they recommend the inclusion of acoustic immittance testing as part of each evaluation, these guidelines caution that acoustic immittance data alone are not sufficient for middle-ear assessment (ASHA, 1991).

The results of the present study do not support the use of wave I latency-based predictions of conductive component for individual patients. Rather, as is the standard for behavioral audiometry, direct measures of cochlear sensitivity should be obtained by recording the ABR to bone-conducted stimuli.

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