Effects of Cochlear Hearing Loss on the ABR Latencies to Clicks and 1000 Hz Tone Pips

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Abstract

High-frequency hearing losses can substantially confound the interpretation of click-evoked auditory brainstem responses (ABRs). One method proposed to circumvent the problem is to use frequency-specific tone pips to stimulate equivalent areas on the basilar membrane in normal and pathologic groups, or in both ears of asymmetrically impaired patients. This retrospective study investigated the ABRs to clicks and 1000-Hz tone pips from 90 asymmetrically impaired subjects with cochlear pathology. The 4000 Hz threshold significantly affected the wave V latencies from both clicks and tone pips for the most severely impaired subjects. The wave V latencies were highly correlated between ears for both stimuli, but the correlation was higher with the 1000-Hz tone pips. It was concluded that the use of 1000-Hz tone pips can supplement the interpretation of click-evoked ABRs, particularly in patients whose 2000- and/or 4000-Hz thresholds are worse than 75 dB HL.

Key Words: Auditory brainstem response (ABR), cochlear hearing loss, wave V latency, asymmetrical hearing

One difficulty in obtaining auditory brainstem responses (ABRs) from patients with high-frequency hearing losses is that the hearing loss shapes the effective spectrum of the click. The result is that different areas on the basilar membrane are stimulated depending on the configuration and degree of the hearing loss (Aran et al., 1975; Elberling and Salomon, 1976; Coats and Martin, 1977). The different areas of the basilar membrane, in turn, produce different latencies, which leads to a diagnostic dilemma when determining whether a delayed latency is due to a cochlear or retrocochlear pathology, especially in cases in which wave I is absent. Difficulties are encountered in comparing ABR latencies of hearing-impaired patients to norms collected on normal-hearing subjects, as well as in comparing interaural latencies of patients with unilateral or asymmetrical hearing losses.

Various methods have been suggested to compensate for the delay caused by cochlear pathology, although none has achieved widespread use because of relatively poor predictive results for individual cases (Fowler and Durrant, in press). These methods include adding a correction factor to the click-evoked latencies (Selters and Brackmann, 1977; Jerger and Mauldin, 1978; Hyde and Blair, 1981) and using electrocochleographic methods to elicit wave I (Durrant, 1986; Ferraro and Ferguson, 1989). An alternative method suggested for circumventing the problems of click stimuli in hearing-impaired subjects is to use tone pips in an attempt to stimulate equivalent areas of the basilar membrane in normal and pathologic ears (Fowler and Noffsinger, 1983; Telian and Kileny, 1989).

The following is a retrospective study of patients seen for routine ABRs in the Audiology Section at the VA Medical Center, Long Beach, California in 1983 and 1984. The purpose of the investigation was to evaluate the clinical utility of 1000-Hz tone pips and clicks for eliciting the ABR in patients with asymmetrical hearing loss presumably of cochlear origin.

METHOD

Subjects were 90 patients referred for ABR testing because of asymmetrical hearing...
loss or tinnitus. The subjects were male and ranged in age from 21 to 82 years, with a mean age of 56 years. The results of audiologic evaluations, consisting of air- and bone-conduction thresholds at octave intervals from 250 to 8000 Hz, word recognition at PBm . and 90 dB HL, tympanometry, and acoustic reflex thresholds and adaptation, were consistent with cochlear pathology. Subjects with confirmed retrocochlear pathology were not included in the subject sample.

Stimuli were rarefaction clicks and 1000-
Hz tone pips. Clicks were produced from 100-
µsec rectangular pulses through matched TDH-
39 earphones in MX-41/AR cushions. The clicks
were delivered to 30 subjects each at 75, 85, or
95 dB nSL (normalized sensation level*), which
were equivalent to 105, 115, and 125 dB peSPL
(peak equivalent sound pressure level). The
clicks were presented at equal levels for both
ears at an overall level ≥15 dB above the audiometric threshold at 4000 Hz in the worse ear or
at 95 dB nSL if the 4000-Hz threshold was
≥80 dB HL. The choice of click level, therefore,
ensured that the high-frequency audiometric thresholds would be higher for subjects receiving the higher level stimuli. The three subject groups are referred to by click level (i.e., the 75 group, 85 group, and 95 group). Tone pips at 1000 Hz (1-msec linear rise-fall times, 0-
msec plateau, fixed onset phase) were delivered
at 75 dB nSL (100 dB peSPL) to all subjects.
This level was ≥15 dB above the 1000-Hz thresh-
hold in the poorer ear. The acoustic spectra for
the clicks and 1000-Hz tone pips are given in
Figure 1.

The ABR was recorded with gold cup elec-
trodes attached to the skin at the vertex (non-
inverting input), ipsilateral earlobe (inverting input), and at the forehead (ground). Inter-
electrode impedance was ≤5000 Ω and equal
(±1000 Ω). Physiologic activity was filtered (Nicolet, Model 501-A) between 150 and 3000
Hz (3-dB down points, 12-dB/octave rejection rates). Responses were averaged (Nicolet, Model 812) over 3000 trials in a time window of 10.48
msec. All responses were replicated to ensure reliability. Latencies were measured from stimu-
lus onset to the positive peak of the wave. Averaged latencies from the two replications
were used in the data analysis.

*Sensation level, as defined by Sonn (1969), is "the pressure
level of the sound in decibels above its threshold of audibility
for the individual subject or for a specified group of subjects." The
prefix 'n' denotes that a group of normal hearing
subjects is used as the referent.

Figure 1. The average acoustic spectra (N = 32) for the
clicks (upper panel) and 1000 Hz tone pips (lower panel).
Spectra were obtained through TDH-39 earphones with
a spectrum analyzer (Brüel & Kjær, Type 2033).

RESULTS

The mean audiometric thresholds for oc-
tave intervals from 500 to 4000 Hz for the
30 subjects in each group are shown in Figure 2.
Each group was characterized by a sloping high-
frequency hearing loss, and as expected, this
slope was greater for the subject groups requir-

Figure 2. The means (squares) and ranges (bars) for the
auditory thresholds for the three groups of subjects. Open
symbols are thresholds from the better ear and filled
symbols are thresholds from the poorer ear.
Table 1 Latencies of Waves I and V and the I-V Latency Differences

<table>
<thead>
<tr>
<th>Group</th>
<th>Wave 1</th>
<th>Wave V</th>
<th>I-V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clicks</td>
<td>1.87 (0.17)</td>
<td>6.00 (0.32)</td>
<td>4.10 (0.29)</td>
</tr>
<tr>
<td>65</td>
<td>1.81 (0.21)</td>
<td>5.96 (0.22)</td>
<td>4.17 (0.26)</td>
</tr>
<tr>
<td>95</td>
<td>2.15 (0.53)</td>
<td>6.12 (0.36)</td>
<td>3.98 (0.43)</td>
</tr>
<tr>
<td>All</td>
<td>1.92 (0.35)</td>
<td>6.03 (0.33)</td>
<td>4.06 (0.35)</td>
</tr>
<tr>
<td>1000-Hz Tone Pips</td>
<td>2.87 (0.24)</td>
<td>6.82 (0.31)</td>
<td>3.95 (0.28)</td>
</tr>
<tr>
<td>65</td>
<td>3.03 (0.32)</td>
<td>6.99 (0.29)</td>
<td>3.95 (0.29)</td>
</tr>
<tr>
<td>95</td>
<td>3.12 (0.37)</td>
<td>7.15 (0.36)</td>
<td>4.00 (0.27)</td>
</tr>
<tr>
<td>All</td>
<td>3.00 (0.33)</td>
<td>6.99 (0.35)</td>
<td>3.97 (0.28)</td>
</tr>
</tbody>
</table>

Means and standard deviations (in parentheses) in milliseconds.

The means and standard deviations (in parentheses) in milliseconds of higher stimulus levels. The group means do not demonstrate the asymmetries because different audiometric frequencies were asymmetrical in each subject.

Wave V was present in all conditions for all 90 subjects, whereas wave I was absent in 25 subjects with the click stimuli and 31 subjects with the 1000-Hz tone pips. The difference in numbers of wave I present for the two stimulus types, evaluated with a chi-square analysis (Guilford, 1965), was not significant. The 4000-Hz thresholds of the subjects missing wave I for either stimulus ranged from 10 to 105 dB HL. Only eight subjects, all in the 95 group, were missing wave I for both stimulus conditions. The mean 4000-Hz threshold for these eight subjects was 86 dB HL, with a range of 65 to 105 dB HL.

The means and standard deviations for wave I and V latencies and the I to V latency differences for each subject group and for the total group for both clicks and 1000-Hz tone pips are given in Table 1. Two-way analyses of variance (ANOVA) (Northwest Analytical, 1986) with one repeated measure (subject group by stimulus type) indicated the same significant variables for both waves I and V. Significant group differences for the wave latencies (Table 2) precluded pooling of data for the three subject groups for most of the statistical analyses. As expected, the latencies elicited by clicks and 1000-Hz tone pips were significantly different. The interaction between the latencies for subject group and stimulus type was also statistically significant. For wave V, for example, the latency difference between the 75 and 95 groups was 0.12 msec for clicks and 0.33 msec for the 1000-Hz tone pips. The increase in latencies for the 1000-Hz tone pips across subject groups, which was not complicated by different stimulus levels (as were the click latencies), demonstrates that an increasing latency delay was imposed by an increasing hearing loss.

A linear regression analysis (Northwest Analytical, 1986) indicated that the latency of wave V varied significantly with the latency of wave I. For all subjects having both waves I and V, the wave I latency contributed less variability to the wave V latency for the clicks ($r^2 = 0.20$; $F(1, 158) = 38.54; p < .01$), than for the 1000-Hz tone pips ($r^2 = 0.41; F(1, 147) = 100.52; p < .01$). Bivariate plots of the relations between wave I and V latencies for each subject group and both stimuli are shown in Figure 3. The highest correlations were in the 95 group, for which the hearing loss was the greatest.

The wave V latencies from both the clicks and 1000-Hz tone pips were subjected to a linear regression analysis with respect to behavioral thresholds between 500 and 4000 Hz for all three subject groups. The linear regression lines deviated significantly from 0 (Table 3) only in the 95 group and only for the 4000 Hz thresholds. These relations are shown in Figure 4, in which the wave V latencies increased with increases in the auditory threshold at 4000 Hz for waves V elicited by both clicks and 1000-Hz tone pips. The 4000-Hz thresholds contributed 41 percent of the variability in the click-evoked wave V latencies, but only 17 percent of the variability in the 1000-Hz tone pip-evoked latencies, indicating the greater effect of the high-frequency hearing loss on the click-evoked latencies.

Similarly, only in the 95 group, as the interaural threshold differences increased for both 2000 Hz and 4000 Hz, significant increases occurred in the interaural wave V latency differences from both clicks and 1000-Hz tone pips (see Table 3). This relation is depicted in Figure 5, in which the interaural wave V latency differences are shown increasing with interaural

Table 2 Results of the ANOVAs for the Latencies of Waves I and V for Subject Group versus Stimulus

<table>
<thead>
<tr>
<th></th>
<th>F Ratio</th>
<th>df</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subject group</td>
<td>20.68</td>
<td>2.177</td>
<td>&lt; .01</td>
</tr>
<tr>
<td>Stimulus</td>
<td>1202.92</td>
<td>1.137</td>
<td>&lt; .01</td>
</tr>
<tr>
<td>Interaction</td>
<td>7.04</td>
<td>1.137</td>
<td>&lt; .01</td>
</tr>
<tr>
<td>Wave V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subject group</td>
<td>8.79</td>
<td>2.177</td>
<td>&lt; .01</td>
</tr>
<tr>
<td>Stimulus</td>
<td>3726.35</td>
<td>1.177</td>
<td>&lt; .01</td>
</tr>
<tr>
<td>Interaction</td>
<td>18.40</td>
<td>2.177</td>
<td>&lt; .01</td>
</tr>
</tbody>
</table>
threshold differences for both 2000 Hz and 4000 Hz. The 2000-Hz and 4000-Hz threshold differences accounted for 23 percent and 52 percent, respectively, of the variability in interaural latency differences for click responses. In contrast, the 2000- and 4000-Hz threshold differences each accounted for 27 percent of the variability in interaural latency differences for 1000-Hz tone pips. Thus, the wave V latencies from clicks were more dependent on both absolute thresholds and interaural threshold differences than were the wave V latencies from 1000-Hz tone pips, and these dependencies were only significant for the severe high-frequency hearing losses. Of all the frequencies tested, 4000 Hz exerted the greatest effect on the wave V latencies.

The wave V latencies between the left and right ears were subjected to a linear regression analysis. For the three subject groups combined, the left and right ears were significantly correlated both for clicks ($r^2 = 0.67; F[1, 88] = 177.41; p < .01$) and for the 1000-Hz tone pips ($r^2 = 0.79; F[1, 88] = 343.93; p < .01$). The lesser interaural correlation for click latencies than for 1000-Hz tone pip latencies is undoubtedly a result of the greater dependence of the click latency on the 4000-Hz auditory threshold, at which most of these subjects had asymmetrical hearing losses. The interaural latency relations for wave V for both clicks and 1000-Hz tone pips are shown in Figure 6.

**DISCUSSION**

The use of tonal stimuli has been proposed as a method for circumventing the latency

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**Figure 3** Bivariate plots of the wave I and wave V latencies for the 75 group (upper panels), 85 group (middle panels), and 95 group (lower panels) for the click (left panels) and 1000 Hz tone pip (right panels) stimuli. Lines through the data are the best fit regression lines.

**Figure 4** Bivariate plots of the wave V latency and 4000-Hz thresholds from the 95 group. The left panel includes latencies from wave V elicited by clicks and the right panel includes latencies from wave V elicited by 1000-Hz tone pips. The lines through the data are the best fit regression lines.

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**Table 3** Linear Regression Analyses for the 95 Group

<table>
<thead>
<tr>
<th>Comparison</th>
<th>$r$</th>
<th>$r^2$</th>
<th>$F$</th>
<th>df</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Click V vs 2000 Hz</td>
<td>0.32</td>
<td>0.10</td>
<td>6.53</td>
<td>1.58</td>
<td>$p &gt; .01$</td>
</tr>
<tr>
<td>Click V vs 4000 Hz</td>
<td>0.64</td>
<td>0.41</td>
<td>40.05</td>
<td>1.58</td>
<td>$p &lt; .01^*$</td>
</tr>
<tr>
<td>1000 Hz V vs 2000 Hz</td>
<td>0.24</td>
<td>0.06</td>
<td>3.52</td>
<td>1.58</td>
<td>$p &gt; .01$</td>
</tr>
<tr>
<td>1000 Hz V vs 4000 Hz</td>
<td>0.41</td>
<td>0.17</td>
<td>12.16</td>
<td>1.58</td>
<td>$p &lt; .01^*$</td>
</tr>
<tr>
<td>Relative</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Click V vs 2000 Hz</td>
<td>0.48</td>
<td>0.23</td>
<td>8.57</td>
<td>1.26</td>
<td>$p &lt; .01^*$</td>
</tr>
<tr>
<td>Click V vs 4000 Hz</td>
<td>0.72</td>
<td>0.52</td>
<td>30.92</td>
<td>1.26</td>
<td>$p &lt; .01^*$</td>
</tr>
<tr>
<td>1000 Hz V vs 2000 Hz</td>
<td>0.52</td>
<td>0.27</td>
<td>10.44</td>
<td>1.28</td>
<td>$p &lt; .01^*$</td>
</tr>
<tr>
<td>1000 Hz V vs 4000 Hz</td>
<td>0.52</td>
<td>0.27</td>
<td>10.34</td>
<td>1.28</td>
<td>$p &lt; .01^*$</td>
</tr>
</tbody>
</table>

*Significant at $p < .01$

**Absolute** refers to the absolute wave V latencies compared to 2000- and 4000-Hz audiometric thresholds, and **Relative** refers to the interaural wave V latency differences compared to the 2000- and 4000-Hz threshold differences.
delays imposed by high-frequency hearing losses on click-evoked ABRs. The present study indicates that this method has some advantages, but does not completely alleviate the problem. The use of the 1000-Hz stimuli was not necessary in the subjects with 2000-Hz and/or 4000-Hz auditory thresholds below 80 dB HL. In these subjects, the ABR stimulus was ≥20 dB relative to the auditory threshold at 4000 Hz and the click-evoked wave V latencies were within normal limits.

In the 95 group, some of the high-frequency hearing losses were sufficiently severe to prolong the wave V latencies elicited by clicks and by 1000-Hz tone pips. The effect of the 4000-Hz thresholds is expected in the click-evoked ABR because neurons that respond to the high-frequency components of the stimuli dominate the latency of the click-evoked ABR (Don and Eggermont, 1978; Fowler, in press). Because

![Figure 5](image)

**Figure 5** Bivariate plots of the interaural wave V latency difference and interaural threshold differences for the 95 group. The latencies from clicks (upper panels) and 1000-Hz tone pips (lower panels) are shown with the interaural threshold differences from 2000 Hz (left panels) and 4000 Hz (right panels). Best fit regression lines are shown.

Although the latencies of waves I and V were positively correlated, wave I contributed only 20 percent of the variability to the latency of wave V for click stimuli and 41 percent for 1000-Hz stimuli. Among the subject groups, the highest correlations were in the 95 group, in which the high-frequency hearing losses were the greatest. Further, I-V latency differences were shortest for the 95 group with clicks, but equal for all three subject groups with the 1000-Hz tone pips. These results are consistent with three previous indications that the click-evoked wave I is derived from higher frequency responses than is wave V. First, Don and Eggermont (1978) demonstrated the different frequency responses of waves I and V by noting that wave I disappeared sooner than wave V as the derived-band ABRs decreased in frequency. Second, Coats and Martin (1977) reported reduced I-V latency differences in some subjects with high-frequency cochlear hearing losses. In these subjects, the click responses were derived from lower frequencies than in normal-hearing subjects. Third, Fowler and Noffsinger (1983) found shorter I-V latency differences in normal subjects for ABRs evoked by lower-frequency tone pips as compared to higher-frequency tone pips. In the latter two cases, a decrease in the effective stimulus frequency caused a greater prolongation of wave I than of wave V.

One disadvantage in using the tone pips is the qualitative waveform degradation that can sometimes result from the longer rise time in the tone pips than in the clicks. This degradation is expected to affect elderly subjects and...
those with hearing losses, because the waveforms in these subjects already have reduced amplitudes relative to those of young normal-hearing subjects. This degradation may compromise waveform identification and accuracy in identifying peak latencies, and thus may limit the usefulness of tonal stimuli in some subjects.

A further, and perhaps more significant, disadvantage of the use of tone pips is the possibility that low-frequency tone pips may reduce the sensitivity of the ABR to retrocochlear pathology compared to its sensitivity with clicks or high-frequency tone pips. Clemis and McGee (1979) reported a diagnostically significant difference in wave V latencies to tone pips at various frequencies in only 1/17 patients with acoustic neuromas. That case, however, was the only one in which all interaural wave V latency differences were under 1.0 msec. Retrocochlear pathology that exerts lesser effects on the wave V latencies is more likely to be confused with cochlear pathology, and therefore, is the targeted patient group for the use of tonal stimuli. Fowler and Noffsinger (1983) reported that in retrocochlearly impaired subjects, wave V was more delayed with 4000-Hz stimuli than with 2000-Hz stimuli, and that this discrepancy was exacerbated with faster stimulation rates. This finding suggests that higher-frequency tone pips or clicks may be more sensitive in identifying retrocochlear disorders than are lower-frequency tone pips.

Telian and Kileny (1989) found that 1000-Hz tone pip ABRs were useful in confirming the diagnosis of acoustic neuroma made by click-evoked ABR in 17 patients with high-frequency sensorineural hearing losses. In many of these patients, the abnormally long interaural wave V latency differences with click stimuli were considered to be at least partially caused by the severity of the high-frequency hearing losses. The abnormally long interaural differences from 1000-Hz tone pips, however, were attributed to neural pathology because the 1000-Hz thresholds were better than the higher-frequency thresholds, and thus, presumably were less likely to produce a cochlear delay. Further studies that compare the success rate in identifying retrocochlear lesions with clicks and tone pips of various frequencies are warranted.

In summary, the use of 1000-Hz tone pips to elicit the ABR is helpful in distinguishing between cochlear and retrocochlear pathology in some cases of high-frequency, and particularly asymmetrical, sensorineural hearing loss. Generally, the use of clicks is sufficient if the audiometric threshold at 4000 Hz is less than 80 dB HL and the stimulus is delivered at least 20 dB above the audiometric threshold at 4000 Hz. For patients with more severe cochlear hearing losses, the supplemental use of 1000-Hz tone pips can reduce the number of equivocal ABRs if only click stimuli are used. Still to be determined is the likelihood that cases of retrocochlear pathology will fall within normal limits with low-frequency tonal stimuli, but beyond normal limits with clicks or high-frequency tonal stimuli. Further research is necessary to determine the comparative diagnostic sensitivity of the ABR elicited by clicks and tone pips at various frequencies.

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REFERENCES


