Adaptation of the Auditory Brainstem Response: Effects of Click Intensity, Polarity, and Position

Bopanna B. Ballachanda*  
George Moushegian†  
Robert D. Stillman†

Abstract

The aim of this research was to study the effects of several stimulus parameters on adaptation characteristics of the auditory brainstem response (ABR). Recordings were obtained from normal hearing adults to separate trains of 5 rarefaction and 5 condensation clicks with interclick intervals of 10 msec and intertrain intervals of 500 msec at three intensities. Absolute latencies for waves I, III, and V were essentially unchanged by polarity; latency shifts, however, were induced by parametric manipulations of click intensity, polarity, and position in the train. Furthermore, variations in ABR wave morphology appeared with changes in intensity and polarity. Adaptation, as measured by amplitude, was considerable; the measures of adaptation, however, were not related in a simple manner to the latency shifts. The findings indicate that adaptation of the ABR is a consequence of an interplay of central and peripheral processes to click polarity, sequence, and intensity. Finally, the results provide evidence that when fast stimulus presentation rates are used to estimate thresholds rapidly, one must be aware that certain stimulus parameters can alter the ABR waveforms.

Key Words: Auditory brainstem response (ABR), click polarity and intensity, adaptation to click trains

Auditory brainstem responses (ABRs) are a series of scalp-recorded electrical potentials of neural activity generated within the auditory nerve and nuclei and tracts of the lower brainstem during the first 10 msec after a click stimulus (Jewett et al, 1970; Jewett and Williston, 1971). At rapid stimulation rates, the amplitudes of these potentials are attenuated and the latencies prolonged, a phenomenon referred to as adaptation. Investigations using trains of clicks as stimuli indicate that adaptation is complete by the third or fourth click and that it follows an asymptotic pattern (Thornton and Coleman, 1975; Don et al, 1977; Tietze and Gobsch, 1980). Furthermore, since ABR latencies and amplitudes are differentially altered by stimulus rate, both peripheral and central mechanisms must be involved (Thornton and Coleman, 1975). In support of this, Tietze and Gobsch (1980) reported that the latency shifts to a train of clicks are not the same for waves I, III, and V. Don et al (1977) allowed that differences in the ABR could be a consequence of fatigue or adaptation, but argued that the relative contribution of peripheral and central effects could not be determined.

To elicit the ABR, either a rarefaction or condensation click may be used (Cann and Knott, 1979). Animal studies have established that click polarity affects the amplitudes and latencies of cochlear nerve responses (Peake and Kiang, 1962; Kiang et al, 1965). In early ABR studies, click polarities were randomized or alternated to minimize contamination by stimulus artifacts (Terkildsen et al, 1973; Rosenhamer et al, 1978). Stockard et al (1979) wrote that wave V latencies are not affected by polarity. Others have reported, however, that
click polarity may significantly affect amplitude, morphology, and interpeak latencies of all waves of the ABR (Borg and Lofqvist, 1982; Maurer, 1985). Alterations in I-V interpeak latency and V/I amplitude ratios, for instance, occur because wave I latencies and amplitudes are particularly sensitive to click polarity (Stockard et al, 1978, 1979, 1983). Although there are apparent differences in ABR responses to rarefaction and condensation clicks, these stimuli, except for their initial effect on the earphone diaphragm, are spectrally and perceptually identical. Whether variations in the ABR waveforms to click polarity simply reflect the effects of basilar membrane deflections or are also a consequence of differential activation of lower brainstem nuclei and their pathways is unknown.

Thornton and Coleman (1975) reported varying effects of intensity on adaptation to click trains. More adaptation occurred for lower intensities (60 dB) than for high (80 dB). They suggested that this may be a consequence of low- and high-threshold reception systems.

The present study was designed to investigate the effects of stimulus parameters on adaptation of the ABR. Rarefaction and condensation clicks trains at several intensities were utilized to determine whether the resulting waveforms may be used to differentiate peripheral and central adaptation mechanism.

**METHOD**

**Subjects**

Participants in this study were seven graduate students at the University of Texas at Dallas, five females and two males, ranging in age from 20 to 38 years. They had audiometric thresholds of no greater than 15 dB HL (re ANSI, 1969) at octave and interoctave frequencies from 0.25 to 8.0 kHz, and normal middle ear function as evaluated by immittance.

**Equipment and Procedure**

A train of 5 clicks (100 μsec) with an inter-click interval of 10 msec was presented at intervals of 500 msec (about 2/sec) at 30, 60, and 80 dB nHL. The polarities of all clicks in a train were either rarefaction or condensation. The largest peak in the acoustic spectrum of the clicks was in the 3.0 kHz range. Stimuli were monitored electrically on an oscilloscope, and calibrated acoustically with a sound pressure meter; the SPL was 67 dB at the 60 dB nHL presentation level. The rarefaction trains were presented first at all intensities, followed by condensation trains. The stimuli were delivered monaurally to the right ear through electromagnetically shielded earphones (TDH 49) with circumaural cushions (MX-41AR).

The subjects were tested in an electrically insulated sound-treated room while in a relaxed state. Gold-plated cup electrodes were attached at the vertex (positive), the mastoid ipsilateral to the stimulated ear (negative), and the contralateral mastoid (ground); the resistance between electrodes was always less than 5.0 kOhms. The electrical potentials were amplified 10^5 times, bandpassed between 0.3 and 3.0 kHz, and collected at a bin resolution of 50 μsec by a signal averager (Nicolet 1074). Electroencephalographs (EEGs) were monitored on an oscilloscope; voltages greater than 1 volt peak-to-peak were rejected. The waveforms, the result of 1024 averages, were plotted (Hewlett Packard 7035B), and the latencies and amplitudes of waves I, III, and V at 80 and 60 dB nHL determined. Since waves I and III are typically difficult to identify at 30 dB, only wave V amplitudes and latencies were determined and measured at this intensity. Multivariate analyses of variance for repeated measures were performed to ascertain the effects of click position, polarity, and intensity on waveform amplitudes and latencies.

**RESULTS**

**General**

Figure 1 displays examples of ABRs at three intensities to rarefaction and condensation click trains. There are apparent differences in wave morphology and amplitude due to click position in the train for successive responses at a particular intensity. The effect of click sequence is more evident at 80 and 60 dB than at 30. The responses to the first click, for instance, are more sharply defined than those to the remaining clicks in a train. In addition, responses at opposite polarities are not comparable. The waveforms from all the other subjects were similar to these and suggest that: (1) rarefaction and condensation clicks evoke many dissimilar waveforms; (2) successive clicks, regardless of click polarity, do not produce invariant responses; and (3) intensity affects the various components of the ABR.
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Figure 1 Auditory brainstem waveforms from one subject to a train of rarefaction (R) or condensation (C) clicks. Vertical dashed lines indicate onset times, 0, 10, 20, 30, and 40 msec of each click in a train.

**ABR Wave Latencies**

Latencies were measured from the onset of each click in the train to the peaks of waves I, III, and V. Whenever wave V or III contained double peaks, latency was measured to the second peak if the amplitude was greater than 50 percent of the first peak. The mean latencies and standard deviations of waves I, III, and V for seven subjects to trains of rarefaction and condensation clicks are plotted in Figure 2. The results demonstrate that click polarity has little effect on the average latencies of the waves. A MANOVA indicated that click polarity did not produce a significant wave V latency shift ($F = 0.41, p = .9$) at any intensity or click position.

The wave V latencies to each click in the train were rank-ordered to determine the effect of click number on the responses (Fig. 3). Clearly, the first click in the train always produced the shortest latencies; and the wave V responses to the fourth click exhibited some recovery.

The mean latency shifts of wave V to each of the clicks are displayed in Figure 4. The results at each of these intensities are not comparable. At 80 dB the latency shifts to the first three clicks increased linearly, followed by a slight recovery to the fourth, and then a further prolongation to the fifth click. Statistical trend

Figure 2 Mean latencies of ABR waves to rarefaction and condensation trains of clicks.

Figure 3 Average rank-order of wave V latencies to 5 click train ($N = 7$).
analysis for the sequence indicated that most of the wave V latency shifts at 80 dB are linear, but cubic and quadratic functions were also uncovered. There were no polarity effects. Adaptation within the click train also occurred at 60 dB; recovery to the fourth click, however, was not present. At this intensity, a differential polarity effect appeared to the fourth and fifth clicks. There was a latency shift to the second click at 30 dB, but essentially no sizable shifts for the remaining clicks in the train.

A similar analysis at 80 dB for wave III (Fig. 5) revealed less adaptation, which essentially asymptoted beyond the second click. Wave III latency shifts, in contrast to those for wave V, were differentially altered by polarity reversals. At 60 dB the latency shifts to rarefaction and condensation clicks were similar, except for the fourth click where a difference appeared consequent to polarity. The latency shifts of wave I were minuscule. They were analyzed, nonetheless, and are displayed in Figure 5.

Finally, the grouped response variability was assessed to establish whether subjects consistently yielded earlier latencies to rarefaction than to condensation clicks (Stockard et al., 1978). Also of interest was the maximum latency difference between rarefaction and condensation clicks, by subject, for all three waves at several intensities (Table 1). It is apparent that the influence of click polarity on all waves varies by subject. This is not evident, however, when the data from all subjects are averaged.

Statistical analysis of the amount of adaptation for waves V, III, and I at each intensity support the following conclusions:

1. There was no significant effect for the intensity (p > .05).
2. There was a significant difference between the amount of adaptation for wave V as compared to wave I at both 80 dB (p = .005) and 60 dB (p = .04).
Table 1 Waveform Latencies to Condensation and Rarefaction Clicks

<table>
<thead>
<tr>
<th>Click Sequence</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 dB nHL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wave V</td>
<td>57 (0.35)</td>
<td>28 (0.55)</td>
<td>57 (0.30)</td>
<td>57 (0.45)</td>
<td>57 (0.40)</td>
</tr>
<tr>
<td>Wave III</td>
<td>42 (0.40)</td>
<td>71 (0.50)</td>
<td>71 (0.35)</td>
<td>71 (0.35)</td>
<td>71 (0.30)</td>
</tr>
<tr>
<td>Wave I</td>
<td>57 (0.20)</td>
<td>28 (0.35)</td>
<td>57 (0.40)</td>
<td>28 (0.25)</td>
<td>57 (0.50)</td>
</tr>
<tr>
<td>60 dB nHL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wave V</td>
<td>28 (0.35)</td>
<td>42 (0.15)</td>
<td>42 (0.20)</td>
<td>42 (0.40)</td>
<td>57 (0.50)</td>
</tr>
<tr>
<td>Wave III</td>
<td>42 (0.25)</td>
<td>42 (0.50)</td>
<td>42 (0.55)</td>
<td>57 (0.70)</td>
<td>42 (0.30)</td>
</tr>
<tr>
<td>Wave I</td>
<td>57 (0.35)</td>
<td>57 (0.75)</td>
<td>0 (0.40)</td>
<td>71 (0.30)</td>
<td>71 (0.60)</td>
</tr>
<tr>
<td>30 dB nHL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wave V</td>
<td>42 (0.30)</td>
<td>71 (0.40)</td>
<td>57 (0.30)</td>
<td>42 (0.10)</td>
<td>42 (0.20)</td>
</tr>
</tbody>
</table>

Data are in percent for subjects (N = 7) having earlier waveform latencies to condensation than rarefaction clicks; also illustrated are maximum latency difference values (msec) from subjects between condensation and rarefaction click at 80, 60, and 30 dB nHL.

3. The differences between waves V and III, and waves III and I were not significant (p > .05).

These results suggest that adaptation of each of the ABR waves reflects complicated neural processes, not easily interpreted, that are differentially altered by changes of click position, intensity, and phase.

ABR Wave Amplitudes

The amplitudes of the ABR waves to clicks 2 through 5 in the train were normalized to the peak amplitude of the first click, which was often larger than those evoked by subsequent clicks. Figures 6 and 7 depict the results to the click trains for waves V, III, and I, respectively. The data illustrate effects for click position, polarity, and intensity.

As with latency, the amplitude results are complex and not easily characterized. Wave V amplitudes to the later clicks are smaller at 80 dB than the amplitude to the first click, but sizable differences consequent to click polarity did not occur (see Fig. 6). At 60 dB, however, polarity has a differential influence. Clearly, with rarefaction clicks, amplitudes of responses later in the train are diminished (e.g., third to fifth); whereas the responses to condensation clicks are accentuated. Though the influence of polarity and click sequence persists at 30 dB, the direction of the results is not identical.

Almost all of the data points fall below unity (100%), thus indicating a diminution of the response regardless of polarity.

The normalized amplitudes of wave III and I are shown in Figure 7. At both intensities, the wave III amplitude values to the same stimuli clearly show that click polarity and intensity are interactive factors affecting adaptation of the responses. At the greater intensity, re-

\[ \text{Figure 6 Normalized wave V mean amplitudes of second, third, fourth, and fifth click in train to first click (100%) at 80, 60, and 30 dB nHL. Each datum point is relative to the amplitude of wave V to the first click.} \]
responses to the click train are all attenuated (somewhat more for the condensation than the rarefaction click train). The influence of polarity is reversed when the lesser intensity is presented. Note that only the last click in the condensation train produces a reduced response; conversely, the responses to rarefaction are all diminished, with some recovery for the later clicks. In contrast, the influence of click polarity is inconsistent. Similarly, the results at both intensities do not exhibit an orderly effect due to click sequence.

Multivariate statistical analysis of the amplitude data support the following observations:

1. Regarding wave V, only intensity had a significant effect on amplitude (F = 23.03, p = .0001). Neither polarity (F = 0.00, p = .90) nor click sequence (F = 2.46, p = .07) approached significance at any of the levels used in the experiment.
2. In contrast, wave III amplitudes were significantly affected by all variables: intensity (F = 9.92, p = .01), polarity (F = 8.2, p = .02), and click sequence (F = 5.59, p = .003).
3. In the case of wave I, two of the three stimulus variables produced significant effects: intensity (F = 7.38, p = .03) and click sequence (F = 5.07, p = .004).

**DISCUSSION**

In studying adaptation, Thornton and Coleman (1975) concluded that the ABR waves, which originate within the lower brainstem, adapt differently than the potentials from the auditory nerve. They showed that the extent of adaptation is influenced, as would be expected, by the size of the intervals between clicks in a train. In their study, click polarity was alternated in order to average out the cochlear microphonic. On the basis of the ABR responses to combinations of three intensities and three interstimulus intervals, they postulated the existence of "different adaptation mechanisms for the peripheral and central responses" (p. 406).

Don et al (1977) contended, however, that the relative contribution of peripheral and central structures in adaptation of the ABR, based on latency measures of wave V, could not be ascertained because: "The multiplicity of contrived but reasonable explanations for the latency shift of wave V emphasizes the need for defining in more detail the precise generators of the various components comprising the far-field auditory brainstem response" (p. 194). They argued that differences in amplitude and latency could be a consequence of fatigue, as well as adaptation.

Our results cannot be compared, except in a general sense, to those of Thornton and Coleman (1975) and Don et al (1977) simply because we used polarity as a variable, whereas they did not. In addition, their intensity levels and interstimulus intervals in the click train were not the same as ours. Despite these differences, some of the conclusions are comparable. For instance, our latency and amplitude find-
ings support the view that adaptation phenomena are a consequence of mechanisms that differ peripherally and centrally. We are in agreement with Don et al (1977) that it is difficult to distinguish the factors in central and peripheral adaptation. They believed that a clear understanding of ABR adaptation would not occur until the generators were identified. Our results indicate that latency and amplitude measures of adaptation of waves I, III, and V are not equivalent. In humans wave I has contributions exclusively from cranial nerve VIII, whereas waves III and V have multiple contributions, mostly from brainstem nuclei and tracts (Møller and Jannetta, 1985). Judicial use, therefore, of click stimulus parameters provides insights on mechanisms of adaptation, whether peripheral or central.

The finding that interstimulus intervals of 10 msec can significantly alter the latency and amplitudes of succeeding click-evoked ABR waves suggests that one should avoid the presentation of stimuli as close as 10 msec, particularly in a clinical setting. A recent article by Hamill, Hussung, and Sammeth (1991) reported rapid threshold estimation using “chained-stimuli.” Our results, as well as those of others (Thornton and Coleman, 1975; Don et al, 1977; Tietze and Gobsch, 1980), indicate that adaptation occurs with interstimulus intervals up to 30 to 40 msec at all intensities. In light of these findings clinical implementation of “chained-stimuli” for rapid threshold estimation requires careful and systematic investigation.

Waveform changes attributed to click polarity have been obtained from subjects with high-frequency hearing loss, and those with confirmed neurologic pathology. In the first instance, wave I and V latencies were altered by polarity; whereas in certain neuropathophysiologies, the presence or absence of wave V was dependent on click polarity (Coats and Martin, 1977; Maurer et al, 1980; Borg and Lofqvist, 1981, 1982; Emmerson et al, 1982; Maurer, 1985). Our study provides evidence suggesting that click polarity alters wave latencies in normal-hearing subjects (see Table 1). These variations are sufficiently large to require a fixed click polarity, rather than an alternating one, for clinical testing.

Neurons in the lower brainstem (e.g., cochlear nucleus and superior olivary complex) discharge at high rates for long periods without decrement; while others adapt readily for certain sounds within their response areas (Moushegian and Rupert, 1970a,b). Differences in the adaptation of wave I, III, and V occur to some extent because of these diversities in normal function and the resulting time course of synaptic events. For these reasons, our ABR results should be viewed as evidence that parametric changes in the stimuli differentially affect central peripheral mechanisms.

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REFERENCES


