Auditory Brainstem Response to Tone Bursts in Quiet, Notch Noise, Highpass Noise, and Broadband Noise

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Abstract
This study investigated the effects of tone bursts (1000 Hz, 2000 Hz, and 4000 Hz) in quiet, notch noise, highpass noise, and broadband noise on the identifiability, latency, and amplitude of the auditory brainstem response (wave V). Normal listeners were presented with 40 dB and 80 dB nHL tone bursts having rise-plateau-fall times of 1 msec. Wave V was observed in all subjects at 40 dB and 80 dB nHL for the quiet and noise conditions. The latency findings suggest that responses elicited by the 80 dB nHL tone bursts in quiet were, in part, mediated by regions on the basilar membrane that did not correspond to the center frequency of the tone burst. To increase frequency-specificity, high-level tone bursts (e.g., 80 dB nHL) should be mixed with notch, highpass, or broadband noise. The use of noise conditions for low intensity levels (e.g., 40 dB nHL) does not appear necessary for isolating the response because both the notch and the highpass conditions yielded latencies similar to the quiet condition. Although similar wave V amplitudes were found at all frequencies, amplitudes were smaller for the broadband noise than for the quiet, notch, and highpass conditions. Thus, the latter conditions seem preferred.

Key Words: Auditory brainstem response, normal listeners, tone bursts, notch noise, highpass noise, broadband noise

Auditory brainstem response (ABR) audiometry is useful to estimate auditory thresholds with individuals who cannot be tested using conventional procedures (Jerger and Mauldin, 1978; Stein et al, 1981; Hall, 1984; Davis et al, 1985; Schwartz and Schwartz, 1991). Clicks commonly are used in ABR audiology because they optimize response identifiability (Kileny, 1981; Hayes and Jerger, 1982; van Zanten and Brocaar, 1984; Hood and Berlin, 1986; Gorga and Thornton, 1989). However, clicks are characterized by a broad frequency spectrum that is shaped by the frequency response of the transducer. This lack of frequency specificity does not allow an accurate estimate of audiometric configuration (Jerger and Mauldin, 1978; Hood and Berlin, 1986). Furthermore, clicks complicate comparisons between clinics because an identical electric waveform can yield substantially different spectra among earphones (Weber et al, 1981; Laukli, 1983a). Tone bursts are recommended because they are more frequency specific than clicks and their spectra are not highly dependent on the frequency response of the earphone (Laukli, 1983a). The degree of frequency specificity is dependent on rise, plateau, and fall times; longer durations have narrower bandwidths. However, because ABRs are critically dependent on stimulus onset (Brinkmann and Scherg, 1979; Debruyne and Forrez, 1982), longer durations yield fewer responses and smaller amplitudes. Although it is desirable to test at 500 Hz, several investigators have reported that this frequency yields smaller amplitudes and/or larger intersubject variability than higher frequencies (Don et al, 1979; Hayes and Jerger, 1982; Laukli, 1983b; Gorga et al, 1988; Fjermedal and Laukli, 1989; Beattie and Spence, 1991). Thus, it appears that the most successful tone-burst stimuli for eliciting ABRs are frequencies
of 1000 Hz and above. As a compromise between frequency specificity and response identifiability, tone bursts with rise-plateau-fall times of approximately 1 millisecond (msec) are selected.

Several authors have suggested that an ABR evaluation for auditory sensitivity should include at least one high-frequency stimulus and one low-frequency stimulus (Kileny, 1981; Eggermont, 1982; Jerger et al., 1985; Fjermedal and Laukli, 1989; Gorga et al., 1991). This allows clinicians to construct a two-point audiogram, which serves as a basis for making rehabilitative decisions. Investigators do not agree, however, on preferred stimuli for estimating threshold (Don and Eggermont, 1978; Kileny, 1981; Beattie and Boyd, 1985; Stapells et al., 1985; Hood and Berlin, 1986; Gorga et al., 1988). Some authors suggest using tone bursts in quiet, whereas others recommend mixing tone bursts with highpass, notch, or broadband noises (Picton et al., 1979; Stapells and Picton, 1981; Laukli, 1983b; Beattie and Boyd, 1985; Stapells et al., 1985; Gorga and Thornton, 1989; Purdy et al., 1989). These noises are designed to mask those frequencies outside the center frequency of interest. If masking is not used, the response may be elicited by the side lobes of the tone-burst spectra, especially if linear windows are used (Stapells et al., 1985; Gorga and Thornton, 1989). Additionally, at high stimulus levels the response may be elicited by the upward and, to a lesser extent, downward spread of excitation to frequencies outside the nominal test frequency. This factor is particularly problematic for low-frequency stimuli because of the asymmetry of cochlear mechanics (Wegel and Lane, 1924; Teas et al., 1962; Chung, 1981).

Notch-noise masking is used to prevent both high-frequency and low-frequency areas of the cochlea outside the nominal test frequency from contributing to the response (Picton et al., 1979; Stapells and Picton, 1981; Laukli, 1983b; Beattie and Boyd, 1985; Stapells et al., 1985; Perez-Abalo et al., 1988; Purdy et al., 1989; Beattie and Spence, 1991). Notch-noise masking is limited, however, by the relatively complex instrumentation and by the substantial upward spread-of-masking at moderate and high masking levels (Picton et al., 1979; Chung, 1981; Beattie and Spence, 1991).

Highpass masking noise also has been used to increase frequency specificity (Don and Eggermont, 1978; Kileny, 1981; Laukli, 1983b; Stapells et al., 1985). Highpass noise may provide larger amplitudes than notched noise and, thus, greater response identifiability due to the low-frequency energy on the skirts of the tone burst. Moreover, highpass noise does not contain low-frequency masking noise that may spread into the notch and reduce the signal-to-noise ratio and, consequently, response amplitude and identifiability. Highpass noise also is advantageous because it requires less complex instrumentation than notch noise. However, tone bursts in highpass noise are not as frequency specific as tone bursts in notch noise because the stimulus includes all frequencies below the cutoff frequency.

A third procedure to obtain frequency-specific responses is to mix tone bursts with broadband noise. Broadband noise isolates the response to a particular region of the cochlea corresponding to the nominal frequency of the tone burst. Both the "line busy" and "suppression" hypotheses have been suggested to explain the physiologic mechanisms underlying masking (Pickles, 1982; Stapells et al., 1985). Without broadband noise, tone bursts activate wider areas of the cochlea and the response is derived in part from regions on the basilar membrane outside the nominal test frequency (Picton et al., 1979; Beattie and Boyd, 1985; Stapells et al., 1985; Perez-Abalo et al., 1988). Beattie and Boyd (1985) found no wave V latency differences in the presence of broadband noise and notch noise, and suggested that either procedure may yield more frequency-specific responses than when tone bursts are presented alone. Also, no differences were reported in the number of identifiable responses when tone bursts were presented in broadband noise or notch noise. That is, the additional stimulus energy within the notch did not yield lower thresholds than when the notch was filled with masking noise. These authors concluded that broadband noise is preferable to notch noise because the latter requires more complex instrumentation. However, Picton et al. (1979) observed smaller amplitudes with broadband noise than with notch noise. Therefore, a possible disadvantage of broadband noise is reduced response amplitudes (Burkard and Hecox, 1983) because of the elimination of acoustic energy in the notch (notch noise) or of frequencies below the high-frequency cutoff (highpass noise).

Limited research has compared the effects of tone bursts in quiet, notch noise, highpass noise, and broadband noise on ABRs. Moreover, because of the upward and downward spread-of-masking, the relative effectiveness of the various tone burst-in-noise procedures may be
dependent on intensity (Teas et al., 1962; Chung, 1981). Therefore, the following research question was addressed: Are there differences in detectability, amplitude, or latency of wave V when normal listeners are presented with tone bursts (1000, 2000, and 4000 Hz; 1 msec rise–plateau–fall times) in quiet, notch noise, highpass noise, and broadband noise at 80 dB and 40 dB nHL? Our goal was to assess the relative value of the four types of stimuli to ascertain which stimulus provides the best compromise between frequency specificity and identifiability at both low and high intensities.

METHOD

Subjects

Fifteen normal hearing subjects participated in the study. This group was composed of women ranging in age from 20 to 28 years (mean = 23 years) who reported no history of otoneurologic pathologies. They passed a 20 dB HL (ANSI, 1989) screening at the octave frequencies from 250 Hz to 8000 Hz and had tympanometric peaks within ±50 daPa. The right ear was selected for testing.

Instrumentation and Calibration

The test stimuli were tone bursts with linear rise and fall times of 1 msec and a 1 msec plateau. Therefore, the rise–fall times allowed one complete cycle for 1000 Hz, two cycles for 2000 Hz, and four cycles for 4000 Hz. The tone bursts were produced by a generator (RC Electronics, Model 200BX), directed to an audiometer (Grason-Stadler, Model GSI 16), and then to an earphone (Telephonics, Model TDH-50P) encased in a cushion (Telephonics, Model 51). The frequency response of the earphone is shown in Figure 1. Tone bursts with rarefaction polarity were presented at a repetition rate of 25.6 per second.

Gold-plated electrodes (Grass E5GH) were used to monitor the electric activity that occurred in response to auditory stimulation. These electrodes were connected to a physiologic amplifier (Grass, Model P511K), which provided a gain of 500,000. The responses were shaped by a filter with a bandpass from 30 Hz to 3000 Hz and having rejection rates of 6 dB/octave. The ABR was directed from the physiologic amplifier to the signal averager (RC Electronics). The dwell time was 40 microseconds and the analysis time was 20 msec. The artifact reject was adjusted so that approximately 10 to 20 percent of the trials were discarded (Hyde, 1985).

Acoustic waveforms were obtained by directing the output of the audiometer to the earphone, which was situated on a 6-cc coupler (Quest, Model EC-9A) with an associated microphone (Quest, Model 7023) and sound level meter (Quest, Model 155). The output of the sound level meter was then directed to the signal averager (RC Electronics). The acoustic waveforms revealed linear-shaped envelopes that conformed closely to their nominal durations; there was approximately 0.5 msec of after-ringing.

The acoustic spectra of the tone bursts were obtained by directing the output of the sound level meter to the signal averager. The Power Spectrum Analysis Program (RC Electronics) was used to perform a fast Fourier transform on the tone bursts (resolution = 48 Hz). The results are shown in Figure 2 as A (1000 Hz), B (2000 Hz), and C (4000 Hz). Examination of this figure reveals that although the prominent peaks of energy were present at the nominal center frequencies, substantial acoustic energy was present at both the lower and upper frequency regions.

The tone bursts were calibrated both psychoacoustically and acoustically. Psychoacoustic calibration was obtained by testing 10 normal hearing females with 1000, 2000, and 4000 Hz tone bursts having 1 msec rise–plateau–fall times. Thresholds were obtained using a two-alternative forced-choice method in which the subjects chose which of two intervals contained the stimulus (Penner, 1978; Marshall and Jesteadt, 1986). The intervals were 1 to 2 seconds and the stimulus rate was 25.6 per second. Two dB steps were used and threshold was defined as the 75 percent correct point. Thresholds were averaged across subjects and the means were specified as 0 dB nHL. The intensity of these mean thresholds was deter-
The highpass, broadband, and notch noises were produced by directing white noise from the noise generator (Grass, Model S10) to two cascaded highpass filters (Krohn-Hite, Models 31) and two cascaded lowpass filters (Krohn-Hite, Models 30). Two filters of each type were used to increase rejection rates from a nominal 115 dB/octave to 230 dB/octave. The highpass and lowpass cutoff frequencies were selected with the associated programmable mainframe (Krohn-Hite, Model 3905). The outputs from the lowpass and highpass filters were connected to a custom mixer and the resultant noise was directed to an audiometer (Grason-Stadler, GSI 16) where the noise was combined with the tone bursts.

The frequency responses of the filters were obtained by directing the output of the tone generator (Bruel & Kjaer, Model 1049) to the filters, through the audiometer, and then to the earphone situated on a 6-cc coupler with an associated sound level meter and one-third octave filter (Quest, Models 155 and OB-133). Figure 3 shows that the bandwidths centered around 1000 Hz (450–1600 Hz), 2000 Hz (1400–2800 Hz), and 4000 Hz (2800–5600 Hz) had notch depths of approximately 85 dB. Rejection rates exceeded 175 dB per octave. The same highpass filter frequency settings that were used for the notch noise conditions also were used for the highpass noise conditions (1600 Hz, 2800 Hz, and 5600 Hz).

The noise was adjusted so that it was approximately 15 dB below the level that would mask the tone bursts. That is, effective masking levels of 25 and 65 dB nHL were used with the 40 and 80 dB nHL tone bursts, respectively. Effective masking levels were ascertained by obtaining masked thresholds in broadband noise from 10 normal-hearing subjects. With the broadband noise held constant at 50 and 90 dB SPL, the tone bursts were adjusted initially in 5- to 10-dB steps until the vicinity of threshold was identified. Next, the search for the masked...
threshold began by varying the tone bursts in 2-
dB steps over a range of about 16 dB. The two-
alternative forced-choice procedure previously
described was used and threshold was defined
as the level at which a 75 percent correct score
was achieved on a total of 10 trials at each level.
Thresholds were averaged across subjects to
obtain effective masking levels. When testing
at 80 dB nHL, the broadband noise SPLs (65 dB
nHL effective masking) were 87 dB at 1000 Hz,
88 dB at 2000 Hz, and 94 dB at 4000 Hz. The
noise levels were 40 dB less when testing at
40 dB nHL.

Procedure
The electrode connected to the noninverting
preamplifier input was placed on the vertex, the
electrode connected to the inverting input of the
amplifier was positioned on the neck ipsilateral
to the test ear, and the electrode connected to
the common input was situated on the neck
contralateral to the test ear (Beattie et al,
1986). The neck electrodes were placed 7 cm
below the lower edge of the mastoid. Imped-
ances were less than 5000 ohms and within
1000 ohms of each other. The subjects were
situated in a supine position on a cot located in
a sound-treated suite. The room was darkened
and the subjects were asked to lie as still as
possible. The subjects were tested with tone
bursts in quiet, notch noise, highpass noise, and
broadband noise. Responses were obtained with
tone bursts presented at a high intensity (80 dB
nHL) and a low intensity (40 dB nHL). Testing
was conducted during three sessions, with one
frequency tested per session. The test frequen-
cies and noise conditions were randomized to
guard against order effects.
Responses were considered identifiable if
the waves were judged present by two trained
examiners in at least two of three trials. Wave
V latency was identified as the point just before
the rapid negative inflection, or at the midpoint
of the shoulder when a clear inflection point was
not identifiable. Amplitude measurements were
made from the point corresponding to the la-
tency of wave V to the succeeding trough or
plateau. The number of stimulus repetitions for
each tracing ranged from 3000 to 5000.

RESULTS

Response Detectability
One purpose of this study was to ascertain
the frequency of occurrence of wave V when tone
bursts were presented to normal hearing listen-
ers in quiet, notch noise, highpass noise, and
broadband noise. The results revealed that wave
V was observed in all subjects at 40 dB and 80
dB nHL for the quiet and noise conditions.

Latency
A second purpose of this study was to obtain
wave V latencies for all frequencies and band-
widths. A two-way analysis-of-variance
(ANOVA) for repeated measures was performed
for both the 40 and 80 dB nHL conditions.
Figure 4 illustrates mean latencies in msec
and standard deviations for all three frequen-
cies and bandwidths for 40 dB nHL. Several
observations are evident from this figure. First,
standard deviations decreased as frequency
increased from 1000 Hz (~0.66 msec) to 4000 Hz
(~0.33 msec). Second, the broadband condition
yielded longer latencies than the other three
conditions. For example, at 1000 Hz the mean
latency for the broadband noise was 10.99 msec
while latencies for the quiet, notch noise, and
highpass noise conditions were approximately
10.2 msec. Third, latency increased as frequency
decreased. For example, latencies for the tone
bursts in quiet were 7.6 msec at 4000 Hz and
10.2 msec at 1000 Hz. Fourth, the quiet, notch
noise, and highpass noise conditions yielded
similar latencies at each frequency; latencies
were approximately 7.7, 8.7, and 10.2 msec at
4000, 2000, and 1000 Hz, respectively. Illustra-
tive examples of the waveforms are shown in
Figure 5 for the 40 dB nHL stimuli. Each panel
displays two tracings for each frequency and
bandwidth.
Means and standard deviations for the 80 dB nHL data are displayed in Figure 6. The following observations can be made from this figure. First, standard deviations decreased from about 0.6 msec at 1000 Hz to about 0.2 msec at 4000 Hz. Second, the quiet condition yielded shorter latencies than the other bandwidth conditions. At 1000 Hz the mean latency for the quiet condition was 6.86 msec while latencies for the notch, highpass, and broadband noises were approximately 8.3 msec. Third, latency increased as frequency decreased from 4000 Hz to 1000 Hz. Fourth, the notch, highpass, and broadband noise conditions yielded similar latencies at each frequency. Latencies were approximately 8.5 msec at 1000 Hz, 7.5 msec at 2000 Hz, and 6.9 msec at 4000 Hz. Illustrative examples of the waveforms are shown in Figure 7 for the 80 dB nHL stimuli. Note that the first 3 milliseconds of the tracings are not shown because the electromagnetic stimulus artifact obscured the waveform during this time period.

The ANOVA for the 80 dB nHL stimuli revealed a statistically significant interaction \( F[6,84] = 7.09, p < .01 \), frequency effect \( F[2,28] = 62.78, p < .01 \), and bandwidth effect \( F[3,42] = 109.87, p < .01 \). Tukey’s post-hoc test revealed that latency for the quiet condition was significantly shorter \( p < .01 \) than the notch, highpass, and broadband noise conditions for 1000 Hz and 2000 Hz, and the quiet condition was significantly shorter than the broadband condition for 4000 Hz. Latencies for 4000 Hz were shorter than 1000 Hz for the quiet and noise stimuli \( p < .01 \). Latencies for 2000 Hz were shorter than 1000 Hz for all noise conditions \( p < .01 \). However, latencies for the

For the 40 dB nHL stimuli, the ANOVA revealed no interaction between frequency and bandwidth \( F[6,84] = 0.167, p > .05 \), statistically significant differences among frequencies \( F[2,28] = 203.9, p < .01 \), and significant differences among bandwidths \( F[3,42] = 55.3, p < .01 \). Tukey’s post-hoc test was employed to identify statistically significant differences between means (Bruning and Kintz, 1987). This test revealed that wave V latency for 1000 Hz was significantly longer than those for 2000 Hz and 4000 Hz, and that latency for 2000 Hz was significantly longer than that for 4000 Hz \( p < .01 \). Moreover, the broadband noise condition yielded a longer latency than the other bandwidth conditions \( p < .01 \). No other differences between frequencies or bandwidths were statistically significant.
quiet condition between 2000 Hz and 1000 Hz were not statistically significant (p > .01).

Comparison of the 40 dB nHL stimuli with the 80 dB stimuli reveals three items of interest. First, the 40 dB nHL stimuli had longer latencies than the 80 dB nHL tone bursts, and these differences decreased as frequency increased. For example, the notch noise condition yielded latency differences (40 dB versus 80 dB) of 1.83 msec at 1000 Hz, 1.29 msec at 2000 Hz, and 0.85 msec at 4000 Hz. Second, latency differences between 1000 Hz and 4000 Hz were larger for the 40 dB nHL stimuli. For example, the notch noise stimuli yielded a 1000 Hz to 4000 Hz latency difference of 2.45 msec at 40 dB nHL and 1.47 msec at 80 dB nHL. Third, latency differences between 1000 Hz and 4000 Hz were similar for all conditions at 40 dB nHL (~2.5 msec), and for the noise conditions at 80 dB nHL (~1.5 msec). In contrast, the 80 dB nHL quiet condition yielded a 1000 Hz to 4000 Hz latency difference of only 0.58 msec.

Amplitude

A third purpose of this study was to obtain wave V amplitudes for all frequencies and bandwidths. The 40 dB nHL data are presented in Figure 8, which shows standard deviations and mean amplitudes in nanovolts (nV) as a function of frequency and bandwidth. The figure shows that the broadband condition yielded smaller amplitudes than the other three conditions at 2000 Hz and 4000 Hz. Figure 8 also reveals that the quiet, notch noise, and highpass noise conditions yielded similar amplitudes across frequency (~120 nV).

For the 40 dB nHL stimuli, the ANOVA revealed a statistically significant interaction (F[6,84] = 3.27, p < .01) and bandwidth effect (F[3,42] = 11.08, p < .01). No significant effect for frequency was found (F[2,28] = 0.16, p > .05). Tukey's post hoc test revealed that amplitude for the broadband noise was significantly smaller than the quiet, notch noise, and highpass noise conditions at 4000 Hz, and that amplitude for the broadband noise was significantly smaller than the notch noise at 2000 Hz (p < .01). No other differences among frequencies or bandwidths were statistically significant.

Means and standard deviations for the 80 dB nHL amplitude data are illustrated in Figure 9. The figure shows similar standard deviation.
The ANOVA for the 80 dB nHL stimuli revealed a significant interaction \((F[6,84] = 7.26, p < .01)\) and bandwidth effect \((F[3,42] = 43.80, p < .01)\). There are no statistically significant effects for frequency \((F[2,28] = 0.08, p > .05)\). Tukey's post-hoc test revealed that amplitude for the broadband noise was smaller than the other conditions at 1000 Hz, smaller than the quiet and highpass noise at 2000 Hz, and smaller than the highpass condition at 4000 Hz \((p < .01)\). Furthermore, at 2000 Hz, amplitude for the quiet condition was larger than the three noise conditions \((p < .01)\). No other differences among frequency or bandwidth were statistically significant.

**DISCUSSION**

**Response Detectability**

One purpose of this study was to compare response detectability for wave V to 1000, 2000, and 4000 Hz tone bursts in quiet, notch noise, broadband noise, and highpass noise. The data revealed that response detectability for wave V did not vary for the quiet and noise conditions. We found that wave V was present in all 15 subjects at both 40 and 80 dB nHL in all conditions. These findings are consistent with previous investigators who used procedures similar to those employed in the present study (Kileny, 1981; Stapells and Picton, 1981; Hayes and Jerger, 1982; Gorga et al, 1988).

The present results demonstrate that response detectability for wave V was not affected by stimulus conditions at either 40 or 80 dB nHL. The broadband noise conditions yielded smaller amplitudes, which made detectability more difficult, but responses in the presence of broadband noise were observed in every subject. However, we did not compare identifiability at threshold. Testing at levels less than 40 dB nHL may reveal differences among stimuli.

**Latency**

Latencies decreased when intensity was increased from 40 to 80 dB nHL, and this latency change was greater for the lower frequencies. These findings are consistent with previous research (Kileny, 1981; Stapells and Picton, 1981; Hayes and Jerger, 1982; Beattie and Boyd, 1985; Davis et al, 1985; Stapells et al, 1985; Gorga et al, 1988; Perez-Abalo et al, 1988). Several hypotheses have been advanced to explain this phenomenon. Teas et al (1962) stated that latency is determined by the position at which the cochlear traveling wave first rises above threshold, but that as intensity is increased, this position shifts toward the base with a consequent decrease in travel time. The greater latency shift for the low frequencies with increasing intensity may be explained by an associated greater spread of low-frequency excitation toward the base of the cochlea. Davis (1976) commented that synaptic transmission time is decreased as intensity increases with a resultant decrease in latency. Brinkman and Scherg (1979) suggested that latency is dependent on that point in time at which the traveling wave first rises above threshold. Likewise, Gorga et al (1988) suggested that a certain amplitude may trigger a neural response and that this threshold amplitude will be reached earlier for higher levels of stimulation. Finally, Kileny (1981) suggested that higher intensities are associated with an increase in the traveling wave velocity, which decreases latency because less time is required to reach the place of stimulation on the basilar membrane.

The present study also showed that latency decreased as the frequency increased from 1000 to 4000 Hz. These results are consistent with
previous authors who have used tone bursts in quiet and/or noise conditions (Suzuki et al., 1977; Kileny, 1981; Hayes and Jerger, 1982; Beattie and Boyd, 1985; Davis et al., 1985; Gorga et al., 1988; Purdy et al., 1989). This increase in latency reflects the longer travel time required by low-frequency stimuli to progress to more apical regions of the cochlea (Stapells and Picton, 1981). That is, the place of maximum excitation shifts to the apex of the cochlea as the frequency is increased, thus creating an increase in latency. Also, it is of interest to note that traveling wave velocities are more rapid at the basal end of the cochlea (Eggermont and Odenthal, 1974; Parker and Thornton, 1978). When noise is added to tone bursts to mask the basal areas, the response is derived from the region of the cochlea that corresponds more closely to the nominal frequency of the tone burst.

Slightly longer latencies were observed for broadband noise at 40 dB nHL as compared to the quiet, notch noise, and highpass noise conditions. Although this result was somewhat unexpected (Picton et al., 1979; Beattie and Boyd, 1985), at least three explanations may be offered. First, the shorter latencies for the tone burst in quiet may be due to the additional acoustic energy present in the high-frequency and low-frequency side-lobes. Second, the quiet, highpass noise, and notch noise conditions all contained acoustic energy in the notch region that was not present in the broadband noise. The broadband noise masks tone-burst energy in the notch, which may result in less neural activity related to the stimulus with a consequent increase in latency. Burkard and Hecox (1983) observed increased wave V latency when 60 dB nHL 1000 Hz and 4000 Hz tone bursts were mixed with broadband effective noise levels of only 20 dB to 30 dB. These shifts increased to about 2 msec when the effective masking levels increased to 50 dB. The tendency for broadband noise to increase the latency of ABRs has been verified in subsequent studies (Burkard and Hecox, 1987; Hecox et al., 1989). Burkard and Hecox (1987) concluded that their findings cannot be explained adequately by a shift in place along the basilar membrane. Instead, they hypothesized that the latency shifts occur in the central auditory mechanism, perhaps due to an increase in the time required for synaptic or postsynaptic processes. Third, latency may be dependent on that point in time at which the traveling wave first rises above threshold (Brinkmann and Scherg, 1979). The broadband noise may mask the first cycle or few cycles of the stimulus with a resultant increase in latency. However, the foregoing hypotheses do not explain why latency differences among noise conditions were observed at 40 dB nHL but not 80 dB nHL.

The quiet condition at 80 dB nHL yielded shorter latencies than the noise conditions. Moreover, the 1000 Hz to 4000 Hz latency difference was only about 0.5 msec for the quiet condition but about 1.5 msec for the noise conditions. Also, the latency shift as intensity decreased from 80 dB nHL to 40 dB nHL was greater for the quiet condition than for the noise conditions. For example, for the tone bursts in quiet, latency decreased about 3.0 msec at 1000 Hz, 2.0 msec at 2000 Hz, and 1.5 msec at 4000 Hz. In contrast, the noise conditions decreased latency approximately 2.2 msec at 1000 Hz, 1.5 msec at 2000 Hz, and 1.0 msec at 4000 Hz. These results are consistent with previous research (Picton et al., 1979; Stapells and Picton, 1981; Hayes and Jerger, 1982; Gorga et al., 1988; Beattie and Spence, 1991) and suggest that the responses elicited by the tone bursts in quiet were, in part, mediated by regions on the basilar membrane that did not correspond to the center frequency of the tone burst. Instead, the shorter latencies for the quiet conditions may reflect the contribution of the high-frequency components of the tone burst spectrum and/or the spread of excitation to the higher frequencies. The basal region of the cochlea may contribute to a more synchronized neural response for the quiet condition, as contrasted to the noise conditions that mask the more basal regions of the cochlea (Picton et al., 1979; Stapells and Picton, 1981; Stapells et al., 1985; Beattie and Spence, 1991).

To increase frequency specificity, the present study suggests that notch, highpass, or broadband noise should be used with high-level tone bursts having linear rise–fall times. The use of noise conditions for low intensity levels does not appear necessary for isolating the auditory brainstem response because both the notch and the highpass conditions yielded latencies similar to the quiet condition.

**Amplitude**

Similar amplitudes were found at all frequencies. These results are consistent with Beattie and Boyd (1985) who observed a similar number of responses for 500 Hz, 1000 Hz, and 2000 Hz in quiet, notch noise, and broadband noise. In contrast, Picton et al. (1979) observed
larger wave V amplitudes in notch noise for 1000 Hz tone bursts than for 4000 Hz tone bursts. Studies that have reported amplitudes in response to clicks in notch noise and highpass noise have been quite variable. For example, Beattie and Spence (1991) found that amplitudes increased with increasing frequency whereas Don and Eggermont (1978) reported larger amplitudes at 500 Hz than at 2000 Hz.

With the exception of 1000 Hz at 40 dB nHL, wave V amplitudes were smaller with the broadband noise than amplitudes for the quiet, notch, and highpass conditions. Apparently masking noise desynchronizes some of those neural elements that contribute to the unmasked response, thereby attenuating the whole nerve potential (Stapells and Picton, 1981; Davis and Owen, 1985). Our results are in agreement with Burkard and Hecox (1983) who observed reduced wave V amplitudes when 60 dB nHL with Burkard and Hecox (1983) who observed and Owen, 1985). Our results are in agreement with Burkard and Hecox (1983) who observed and Owen, 1985). Our results are in agreement with Burkard and Hecox (1983) who observed and Owen, 1985). Our results are in agreement with Burkard and Hecox (1983) who observed and Owen, 1985). Our results are in agreement with Burkard and Hecox (1983) who observed and Owen, 1985). Our results are in agreement with Burkard and Hecox (1983) who observed reduced wave V amplitudes when 60 dB nHL 1000 Hz and 4000 Hz tone bursts were mixed with effective masking levels (broadband noise) of only 20 dB. They found that amplitudes decreased from approximately 250 nV in quiet to about 100 nV when the effective masking level was increased to 50 dB. Our results are in contrast with those of Perez-Abalo et al (1988) and Picton et al (1979) who reported that both notch noise and broadband noise produced similar results. Moreover, Beattie and Boyd (1985) found that response detectability was similar for both broadband noise and notch noise. The differences among studies may be due to stimulus variables such as rise–plateau–fall times, filter bandwidths, and/or the intensity relationship between the tone burst and the noise. The bandwidth of the physiologic filters also may have a substantial effect on the ABR (Suzuki and Horiuchi, 1977; Beattie et al, 1984). Moreover, the reader should recall that all of our subjects yielded identifiable responses at 40 dB nHL with the broadband noise, and we did not compare wave V thresholds using the various stimuli.

Because lower amplitudes were found with the broadband noise than with the quiet, notch noise, and highpass noise, the latter conditions seem preferred. At low levels of stimulation, the tone burst in quiet may be preferred because of the apparent frequency specificity and the simplicity of instrumentation. However, at moderate and high intensities, notch and highpass conditions are preferred to the quiet condition because of the improved frequency specificity provided by the masking. The highpass noise is advantageous because it required less complex instrumentation than notch noise, and because the low-frequency spread-of-masking is absent. The notch noise may provide better frequency specificity than highpass noise.

Future studies should investigate the effects of rise–fall times and signal-to-noise ratio on ABRs using highpass, notch, and broadband noises. Moreover, before our procedures can be employed clinically, research is required using tone bursts in quiet and noise with subjects having hearing losses of varying degrees, configurations, and etiologies. Some reports that have studied the electrophysiologic responses of eighth nerve fibers suggest that data from normal hearing systems may not generalize readily to hearing impaired systems (Evans, 1974; Liberman and Kiang, 1978; Kiang et al, 1986). Several investigators have reported that stimulation at moderate-to-high intensities can cause the spread of excitation to adjacent cochlear regions, and that this spread is primarily toward the basal, high-frequency fibers (Kiang et al, 1967; Evans, 1972; Kiang and Moxon, 1974; Liberman and Kiang, 1978). Frequency-threshold (tuning) curves for normal hearing systems show that high-frequency eighth nerve fibers have thresholds at the characteristic (best) frequency that are 40 to 60 dB better than low-frequency thresholds on the tail of the curve (Kiang and Moxon, 1974). That is, the tip-to-tail ratio is approximately 50 dB. Highpass noise may be used to occupy fibers with high characteristic frequencies so that they are unresponsive to low-frequency stimuli. Gorga and Worthington (1983) show that the presence of broadband noise can elevate the frequency-threshold curve for high-frequency fibers but may leave the shape of the curve unaltered. In contrast, cochlear pathology can alter the shape of the frequency-threshold curve in quiet and in noise so that tip-to-tail ratio may be less than 10 dB (Evans, 1974; Dallos and Harris, 1978; Liberman and Kiang, 1978; Liberman and Dodds, 1984; Kiang et al, 1986). Because of the reduced threshold difference between the low and high frequencies, highpass noise may not be effective in masking high-frequency fibers when cochlear pathology is present. Therefore, the application of ABR data obtained on normal-hearing subjects may not be applicable to individuals with hearing impairment (Gorga and Worthington, 1983).

Although the present investigation suggests that mixing tone bursts with notch noise or highpass noise may be feasible procedures for estimating auditory sensitivity, several other
frequency-specific procedures have been suggested. These include tone bursts using Blackman windows (Gorga and Thornton, 1989), early/middle responses (Beattie and Boyd, 1985; Davis et al., 1985), and middle responses (Mendel and Wolf, 1983; Kraus and McGee, 1990). Comparative studies are required using hearing-impaired subjects to assess the relative advantages of these procedures.

REFERENCES


ABR to Tone Bursts in Noise/Beattie and Kennedy


