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ABR Slow Wave and Stimulus Duration

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Abstract

The slow wave (SW) component of the auditory brainstem response (ABR) was recorded in eight young adult subjects of both genders who had normal hearing sensitivity and who exhibited normal behavioral temporal integration (TI) functions. Test stimuli were 500- and 2000-Hz tone bursts, with rise and decay ramps of two periods, ranging in total duration from 2.5 msec to 44 msec. The responses appeared to be made up of contributions from both SW and wave V of the ABR. These composite waveforms showed a progressive, systematic, and statistically significant increase in peak amplitude and latency as a function of stimulus duration at 2000 Hz, but not at 500 Hz. Some pros and cons of recording the SW component during ABR audiometry are discussed, along with other advantageous properties of ABR SW. Additional approaches that may lead to the enhancement of the detectability of short-latency auditory evoked responses are noted.

Key Words: Auditory brainstem response (ABR), auditory evoked potentials, slow wave

The effect of stimulus duration on the auditory brainstem response (ABR) has not been studied extensively in human subjects. Hecox et al (1976) used bursts of white noise varying in duration between 0.5 and 30 msec to elicit short-latency evoked responses in six female subjects who showed normal behavioral threshold temporal summation. They found that, while the latency of wave V increased over the range of durations studied, the amplitude remained virtually constant. The authors concluded that wave V was solely an onset response.

Gorga et al (1984) used 2000-Hz tone bursts varying from 1 to 512 msec in duration to estimate both ABR and behavioral thresholds. They found that ABR thresholds remained relatively constant across all stimulus durations, but behavioral thresholds showed typical temporal integration (TI) functions.

In sharp contrast, Funasaka and Ito (1986) showed a progressive increase in the amplitude and latency of ABR waves V and VI recorded at suprathreshold levels in rodents, and later in human subjects, as the duration of a tone burst at a frequency of 3000 Hz was increased from 5 to 30 msec. A plausible explanation for the discrepancy observed among the cited findings exists; however, before presenting it, a brief review of essential background information may be in order.

We now know that the ABR consists not only of a series of high-frequency waves, as shown by Jewett et al (1970), but also of a slow wave peaking at about the same latency as wave V, and upon which these ripples are superimposed (Davis and Hirsh, 1976; Suzuki et al, 1977; Özdamar, 1980; Klein, 1983). This slow component was clearly observable even in the earliest records of the ABR published by Jewett and his colleagues; however, for the reasons cited below, it has become routine to filter it out in contemporary clinical practice.

Spectral analyses of broadband recordings of the ABR conducted by Boston (1981), Kevanishvili and Aphonchencko (1979), and Suzuki et al (1982) have identified three major ABR components: a low-frequency component within the 50- to 150-Hz range, a mid-frequency component centered at about 500 Hz, and a high-frequency component peaking at about 1000 Hz. While there is a minor lack of agreement among the authors of these studies as to exactly which wave within the Jewett series lies within which band, there is consensus that the low-frequency component corresponds primarily to the slow wave (SW) upon which the faster wavelets are superimposed.

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In the studies cited above, in which conflicting results were obtained as stimulus duration was varied, Hecox et al (1976) and Gorga et al (1984) used a high-pass filter cut-off frequency of 100 Hz, while Funasaka and Ito used a cut-off frequency of 31.5 Hz. It seemed likely that more of the ABR SW component was passed with the lower cut-off frequency than with the higher, suggesting to Funasaka and Ito that the apparent changes that they had observed in the amplitude and latency of waves V and VI might have been attributable to changes in the underlying SW instead. The results of follow-up experiments in rats and in humans led Funasaka and Ito to conclude that the increases in latency and amplitude that they had observed in wave V could, indeed, be accounted for by increases in the latency and amplitude of the underlying slow component.

In summary, the research cited above strongly suggests that increased stimulus duration up to a limit of about 30 msec results in an increase in the amplitude of SW, but not of wave V, of the ABR, and an increase in the latency of both components. We were interested in further exploring the phenomenon described by Funasaka and Ito in human subjects.

METHOD

We designed an experiment to examine ABR SW amplitude and latency as a function of stimulus duration, holding stimulus sound pressure level (SPL) constant. In contrast to Funasaka and Ito (1986), we included both low-frequency (500 Hz) and high-frequency (2000 Hz) stimuli. We chose 500 Hz because it is a frequency where, typically, there is poor agreement between ABR and behavioral thresholds (Hayes and Jerger, 1982; Purdy et al, 1989; Munnerley et al, 1991). We were particularly interested in any implications that the results might hold for routine clinical practice.

Subjects

Eight young adults of both genders and with normal hearing sensitivity and no history of ear disease served as subjects. Behavioral thresholds measured in 1-dB steps were established for each subject for each of the experimental stimuli immediately prior to the initiation of electrophysiologic testing. Mean temporal integration (TI) functions based on these data were compared with expected TI functions based on stimulus temporal relationships. Only those volunteers who showed normal threshold TI functions over the range of stimulus durations used in the experiment were accepted as subjects.

Test Stimuli

Test stimuli were 500-Hz and 2000-Hz tone bursts delivered to the right ear of each subject in alternating polarity through an Etymotic ER-3A insert earphone at a peak SPL of 70 dB and at a repetition rate of 10.9/sec. Rise and decay times of the stimulus envelope were fixed at 2 periods, with plateaus ranging incrementally from 1 to 18 periods for the 500-Hz stimulus and 1 to 56 periods for the 2000-Hz stimulus. This resulted in total durations of 10, 20, 34, and 44 msec for the former stimulus, and 2.5, 5, 20, and 30 msec for the latter. Note that the shortest signal at either test frequency corresponded to an approximation of Gabor's Logon, as described by Davis (1976, pp. 71–72) and as illustrated in Madsen and Hansen (1981, Fig. 2, p. 157). Equivalent durations, as discussed by Dallos and Olsen (1964), were not calculated because they appear to be valid only for stimuli with rise/decay times of 5 msec or longer. Stimulus frequency was counterbalanced, and stimulus duration randomized, across subjects. Mean stimulus sensation levels ranged from approximately 47 dB for the briefest stimuli to 58 dB for the most prolonged.

Recording Procedures

ABR SW potentials were recorded in an electrically shielded sound booth with each subject recumbent and either awake and relaxed or in a state of natural sleep. It should be noted that, while most clinical evidence indicates that sleep has little effect upon the overall ABR waveform, little or no research seems to have addressed the effect of sleep upon the SW component.

Gold cup electrodes were affixed at the vertex (C_z), referred to the right earlobe (A_2), with the left earlobe (A_1) grounded. Full-scale sensitivity of the signal averaging system (Nicolet Viking II, advanced EP software) was 50 microvolts, with artifact rejection set to engage for scalp electrical activity exceeding 90 percent of this figure. Filter passband was 10 to 300 Hz (half power points), with a rejection rate of 12 dB/octave (two-pole Butterworth characteristic). Analysis time was 20 msec using a sampling rate of 10 kHz. Two thousand sweeps were recorded during each run.

Method of Analysis

A baseline was established for each individual ABR SW response by adjusting, off line, the entire trace by the algebraic difference between the mean response amplitude recorded during the first msec poststimulus and 0 nanovolts (nV). Individual values of peak response amplitude, measured with respect to the baseline, and of peak latency, measured with respect to stimulus onset, were determined digitally by cursor. The resulting numerical data were subjected to statistical analysis using the Friedman nonparametric two-way analysis of variance model and the Kendall Coefficient of Concordance, a nonparametric measure of correlation, both described by Siegel (1956). Finally, individual baseline adjusted traces were combined to form grand mean waveforms.

RESULTS

The grand mean ABR SW responses recorded at each duration for the 500-Hz stimulus are shown in Figure 1. Peak amplitude ranged from 411 nV to 498 nV. While mean peak amplitude increased progressively as stimulus duration was increased from 10 to 20 to 34 msec, it declined slightly as stimulus duration was extended to 44 msec. The result of a Friedman analysis of variance (p = .466) showed that the minor differences in amplitude observed across conditions were not statistically significant. A Kendall Coefficient of Concordance (W = 0.106) showed only a loose association of the ranks of amplitudes across test conditions, suggesting that the apparent progression of response amplitude was less than systematic.

Mean peak response latency varied from 9.2 msec to 9.7 msec between shortest and longest stimulus durations, with a value of 9.5 msec shared by the two intermediate durations. The result of a Friedman analysis of variance (p = .142) showed that the differences in peak latency observed across stimulus durations were not statistically significant. A Kendall Coefficient of Concordance (W = 0.227) again showed a weak association across test conditions.

In contrast, the grand mean waveforms recorded at 2000 Hz and shown in Figure 2 demonstrated an orderly and progressive increase in both peak amplitude and peak latency as a function of stimulus duration. Amplitude ranged from 304 nV at a stimulus duration of 2.5 msec to 550 nV at a stimulus duration of 30 msec. The results of a Friedman analysis of variance (p = .001) showed that the differences observed across stimulus conditions were statistically significant. The Kendall Coefficient of Concordance (0.675) suggested a close association of the ranks of amplitudes across conditions. Peak latencies ranged from 7.3 msec to 7.8 msec. The result of a Friedman analysis (p = .011) was statistically significant. The Kendall Coefficient of Concordance (W = 0.467) suggested that the ranks of latencies across test conditions varied systematically.

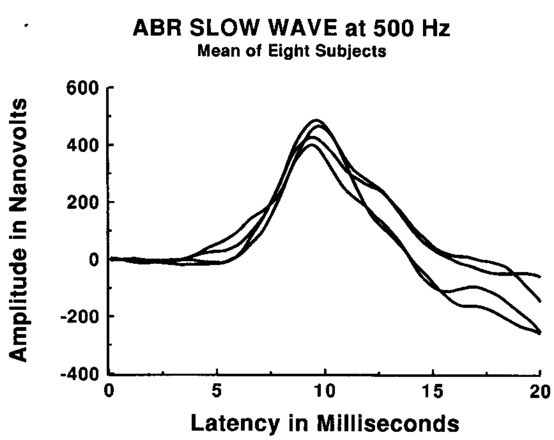

Figure 1 Grand mean waveforms recorded in response to 500-Hz stimuli of varying durations averaged over all eight subjects. The waveforms, in order of increasing peak amplitude, were recorded in response to stimuli with durations of 10, 20, 44, and 34 msec, respectively.

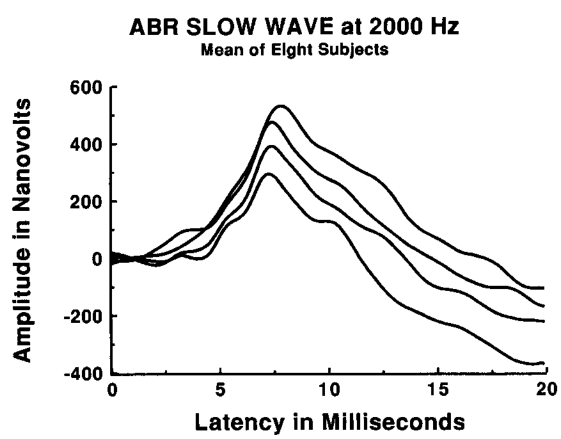

Figure 2 Grand mean waveforms of ABR SW recorded in response to 2000-Hz stimuli of varying durations. The waveforms, in order of increasing peak amplitude, were recorded in response to stimuli with total durations of 2.5, 5, 15, and 30 msec, respectively. They show a progressive increase in mean peak response amplitude as stimulus duration was lengthened.

DISCUSSION

Psychophysics

The reciprocity between stimulus energy and stimulus duration that has been termed temporal summation or TI was first studied in the visual modality by Bloch (1885) more than a century ago. The studies of Hughes (1946) and Garner and Miller (1947) demonstrated the existence of temporal summation in the auditory modality. Miskolczy-Fodor (1956) introduced brief-tone audiometry, a clinical application of the TI phenomenon, but the test enjoyed only limited acceptance by clinicians.

In its most general form, Bloch's Law, as it is called, takes the form of $I \times t = k$ (a constant). Dedicated students of psychophysics will recognize this expression as a simple example of what Stevens (1955) has called a power law (see Marks [1974] for a comprehensive treatment of Stevens' pivotal contributions). Algom and Babkoff (1984) characterized the task of reconciling the repeated and reliable empirical demonstration of the simple linear law describing temporal summation with the existence of a complex and mainly nonlinear auditory system as an enduring problem in auditory theory. Zwislocki (1960) addressed this problem more than 3 decades ago when he formulated a comprehensive deterministic theory of temporal integration. Later, Zwislocki (1969) revised and expanded his theory to include additional findings from auditory physiology.

It is now commonly assumed that power law transformations take place at the periphery, perhaps even at the receptor level. This raises the intriguing question as to whether outer hair cell motility and its efferent control system (Brownell et al, 1985) might affect the power law transformation process by virtue of its influence on inner hair cell function. Further, one might wonder whether this effect might be reflected in TI-like behavior in stimulated otoacoustic emissions (Kemp, 1978).

Possible Electrophysiologic Counterpart to TI

It appears that an electrophysiologic counterpart to behaviorally determined temporal summation may be reflected in the data of Funasaka and Ito (1986), as well as in our own data collected in responses to the 2000-Hz stimulus. However, unlike behavioral manifestations of auditory temporal summation that consistently reflect a time constant of about 200 msec in normal-hearing subjects, electrophysiologic data show a much shorter time constant approximating 30 msec.

Curiously, considering that both the stapedial reflex arc (Borg, 1976) and the generators of early components of the ABR may share certain brainstem structures in common, the visual detection threshold of the acoustic stapedial reflex shows the same 200-msec time constant as behavioral threshold data (Barry and Resnick, 1976), rather than the much shorter 30-msec time constant that characterizes recent electrophysiologic findings. It appears safe to conclude that whatever connection may exist between the temporal-integration-like behavior of ABR SW and behavioral manifestations of temporal summation, it remains obscure.

It should be noted that the finding of a 30-msec time constant associated with an auditory evoked potential may not be unique to ABR SW. Hints of a similar time constant may be found in experiments tapping generators up and down the auditory pathways. Both Onishi and Davis (1968) and Skinner and Jones (1968) showed a consistent increase in the amplitude of late cortical responses, with increasing stimulus duration up to a limit of 25 or 30 msec. Later, Skinner and Antinoro (1971) reported that some of their subjects showed slightly greater amplitude of the early components of the auditory evoked response, which we now know as the middle latency response (MLR), at stimulus durations shorter than 40 msec. Finally, examination of Table II of Hecox et al (1976), which is based on data from four of their six subjects, shows that mean wave V amplitude was greater at a stimulus duration of 30 msec than at 20 msec, which, in turn, was greater than at durations of either 5 or 2 msec. One wonders, given the well-known inherent variability of wave V amplitude, if a statistically significant outcome might, indeed, have been found had the authors run a few more subjects.

Composite Nature of the Responses

Returning to the results at hand, the sharply crested morphology characterizing the responses strongly suggests that more than a little of the energy of wave V, the closest likely spectral neighbor of SW, had penetrated the skirts of the 300-Hz low-pass filter that we used. The wave V component, the amplitude of which was almost certainly enhanced by the use of an abrupt, two-period stimulus rise time, appears to have contributed importantly to the overall morphology of the waveforms, but especially toward defining the locus of the peak amplitude and latency of each response. The use of zero phase shift finite impulse response digital filters with a lower cut-off frequency and a sharper roll-off might have allowed us to record SW more nearly in isolation, but, unfortunately, this facility was not available to us.

The evidence cited in the introductory section, however, suggested that the amplitude of wave V does not increase with stimulus duration (Hecox et al, 1976; Gorga et al, 1984), but that the amplitude of SW does (Funasaka and Ito, 1986). Accordingly, we reasoned that, while wave V, superimposed as it was upon SW, made a contribution to the total peak amplitudes of the responses, this contribution was likely to be invariant across stimulus durations, so that any systematic changes observed in peak amplitude across successive waveforms were solely attributable to corresponding variations in the amplitudes of the underlying SWs.

To explore this speculation, we subtracted the waveform recorded in response to the stimulus of shortest duration from each of the other waveforms, followed by digital smoothing of the resultant waveforms. For the sake of argument, we made the guarded assumption (see Suzuki et al [1986] for a potential caveat) that the short 2-1-2 stimulus would have been likely to elicit a response consisting largely of wave V, which, if it were subtracted from each of the other waveforms, might provide at least a rough indicator of the proportional contribution of SW to each of the other complex waveforms.

Figure 3 shows the results of this manipulation carried out on the waveforms recorded in response to the 500-Hz stimuli. The intertwined, shallow sigmoidal curves are the difference waves associated with durations of 10 and 34 msec. They seem to suggest that SW may have made no more than a minor contribution to the overall amplitude of the composite waveforms. It appears that little or no SW activity occurred in response to the stimulus with a duration of 44 msec. In general, the present data offer little or no support for the use of prolonged stimuli for the audiometric application of ABR at 500 Hz. We have no insight as to why SW activity was so conspicuously absent in these data.

The results obtained in a similar manner on the waveforms recorded in response to the 2000-Hz stimuli are displayed in Figure 4. Here there is an orderly progression of increasing amplitude from bottom to top traces as stimulus duration

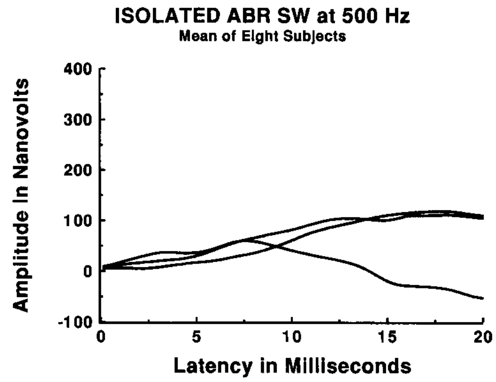

Figure 3 Waveforms resulting from the subtraction of the waveform recorded in response to the 500-Hz stimulus at the shortest duration from those recorded in response to stimuli of longer durations. The difference waves show no pattern of progression in amplitude with increase in stimulus duration. See text for a discussion.

was increased, parallelling the pattern seen in the more complex waveforms shown in Figure 2. This suggested to us that SW contributed importantly to the overall amplitude of the composite waveforms obtained at this test frequency.

Applicability of ABR SW to Clinical Practice

The outcome of our experiment at the stimulus frequency of 500 Hz was not statistically significant. The corresponding decibel difference calculated between the mean response amplitude

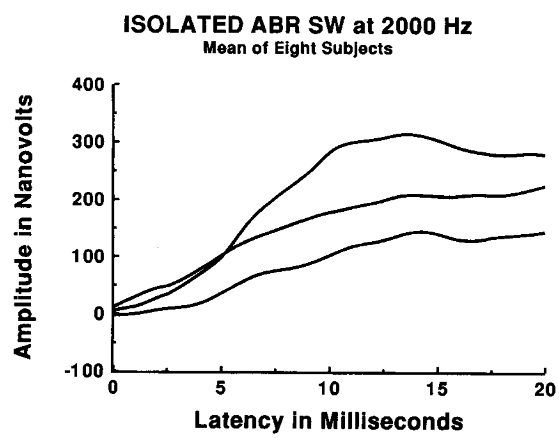

Figure 4 Waveforms resulting from the subtraction of the waveform recorded in response to the 2000-Hz stimulus at the shortest duration from those recorded in response to stimuli of longer durations. The difference waves show an orderly increase in amplitude as a function of stimulus duration. See text for a discussion.

observed at the shortest stimulus duration and the duration producing maximum response amplitude was only 1.7 dB, a value that we considered to be trivial. While the present results are hardly supportive of the use of prolonged stimuli at 500 Hz clinically, it occurred to us, belatedly, that the duration of the two longest experimental stimuli exceeded the expected time constant of 30 msec, possibly resulting in a rollover in response amplitude. Accordingly, the use of prolonged stimuli at a stimulus frequency of 500 Hz might well merit further exploration using a more appropriate set of gradations in stimulus duration.

The finding of a systematic growth of SW amplitude with stimulus duration at a test frequency of 2000 Hz may, on the other hand, prove to be of value in the audiometric application of ABR. Peak amplitude in response to 2000-Hz stimuli initially increased rapidly by 3.6 dB as stimulus duration was increased to 10 msec, and by a total of slightly more than 5 dB at asymptote at about 30-msec duration. Assuming that the same increase in response amplitude observed experimentally at suprathreshold levels extrapolates to responses obtained to stimuli presented at near threshold levels, it seems likely that the near doubling in mean ABR SW peak amplitude observed at the longest stimulus duration might favorably influence the detectability of an ABR response. Or, looked at from the point of view of testing efficiency, an increase in response amplitude of 5 dB suggests that one might be able to achieve the same relative improvement in signal-to-noise (S/N) ratio during averaging with a stimulus of 30 msec in about one-third of the number of sweeps that would be necessary for a brief tone pip.

Taking a slightly different tack, one might try to take advantage of the rapid increase in the peak amplitude of the composite waveform observed as stimulus duration was increased to a duration of 10 msec. Theoretically, the observed 3-dB or more increase in response amplitude should result in an equivalent improvement in S/N ratio for a 10-msec stimulus in only half of the number of sweeps required for a brief tone pip. It would also result in an improvement in frequency specificity of the stimulus by virtue of a reduction in spectral splatter. Arguably, however, this might or might not be a bonus (see Gorga, et al [1991, p. 5] for an interesting insight). A stimulus of 10-msec duration would also permit use of a higher repetition rate than one of 30 msec, permitting a reduction in test time.

On a cautionary note, virtually nothing is known about the influence of auditory pathology upon the relationship existing between temporal integration measured behaviorally and the growth of ABR SW amplitude with stimulus duration. In particular, it has not been established whether the flattening of the behavioral TI function typically observed in the presence of sensorineural hearing loss of cochlear variety is paralleled by a corresponding flattening of the function based upon measures of SW amplitude. If it is, much of the advantage attending the use of prolonged stimuli during audiometry by ABR would be nullified.

Another unknown associated with the SW phenomenon is the mechanism by which stimuli as long as 30 msec in duration affect the amplitude and latency of a waveform that peaks at about 10 msec. Funasaka and Ito (1986) speculated about the influence of late effects attributable to the previous stimulus. Tentative support for their speculation can be drawn from the work of Suzuki et al (1986), who showed that maximum SW amplitude was achieved at a stimulus repetition rate of 40 per sec. This finding is reminiscent of the so-called auditory 40-Hz steady state or event related potential first described by Galambos et al (1981), in which the amplitude of wave V of the ABR appears to be augmented by a component of the MLR elicited by the immediately preceding stimulus. Finally, since its generator is unknown, any diagnostic application of SW has yet to be established.

Other Advantageous Properties of SW

Independent of the above considerations, the reader should be aware that SW exhibits certain other properties that might facilitate ABR audiometry. Klein (1983), for example, using a simultaneous masking tuning curve paradigm, found that SW responses to 500-Hz tone pips were frequency specific up to stimulus levels of at least 80 dB SPL. Kileny (1986) showed that, at least in some individuals, ABR SW at 500 Hz can achieve an amplitude several times that of the faster components. Suzuki et al (1986) found that, while successive waves of the ABR fast components, including wave V, decreased in amplitude as stimulus rate was increased from 8/sec to 90.9/sec, the magnitude of the slow component was hardly affected. The reader should bear in mind, however, that high presentation rates are not compatible with stimuli that approach 30 msec in duration.

Finally, Takagi et al (1985) showed that, when tone bursts with the same 2-1-2 period waveform were used, the amplitude of the slow ABR component remained stable while the fast component decreased in amplitude with decreasing stimulus frequency. They concluded that, "The slow component can be regarded as the most useful index in the ABR for the threshold estimation of hearing" (p. 79).

Caveats

On the negative side, optimal recording of SW, or of a composite ABR response that includes SW, requires a high-pass filter cut-off frequency as low as a few Hz. This opens the recording window wide for the intrusion of neurogenic, myogenic, and electromagnetic interference, all of which overlap ABR SW spectrally. Fortunately, many of these problems can be compensated for by rigorous adherence to good recording technique and by appropriate management of subject behavior.

In summary, it appears that ABR SW manifests several characteristics that may facilitate the audiometric application of ABR, including the increase in response amplitude with stimulus duration demonstrated here. This is not to suggest that other methods of enhancing or augmenting the detectability of early auditory evoked potentials should be ignored.

Some Other Pertinent Findings

Sininger and Don (1989), for example, demonstrated that the electrode montage of vertéx (C_z) to seventh cervical vertebra afforded an advantage of about 4 dB over the conventional vertex to mastoid montage when recording ABRs to stimuli at very low intensities. Another approach relies upon the use of complex stimuli. These have been used in several laboratory experiments seeking electrophysiologic counterparts of the critical band phenomenon. Zerlin (1986) reported an abrupt increase in the amplitude of wave V of the ABR when the bandwidth of a two-tone complex approximated critical bandwidth. Conversely, Sammeth et al (1986) found that ABR responses to two-tone complexes were smaller in amplitude than the responses to a single tone of the same overall SPL. Burrows and Barry (1990) recorded ABRs and MLRs simultaneously in response to two-tone complexes. They found that only component Na of the MLR showed an abrupt increase in amplitude when separation between the probe tones reached a bandwidth consistent with behavioral estimates of the critical band. The inconsistencies among the results of these investigations are likely to be attributable to differences in experimental stimulus and recording parameters. It is clear that these must be resolved before the use of complex stimuli in the clinical setting is contemplated. Improved methods of analysis have also been introduced that have been shown both to enhance and to objectify the detection of auditory evoked responses. Recently, Dobie (1993) reviewed a variety of statistically based methods for estimating evoked potential thresholds.

CONCLUSION

In conclusion, research during the past decade has opened many avenues that might be exploited to enhance the detectability of early auditory evoked potentials. The use of prolonged stimuli may be one of them. It remains to be determined if some or all of these experimental approaches may be successfully combined in a clinically feasible test procedure that will permit closer approximation to auditory threshold than is possible with current methods.

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