Brain Stem Auditory Evoked Response
I. Basic Principles and Clinical Applications in the Assessment of Patients with Nonorganic Loss

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A developing method for testing auditory function and detecting neurological disorders is the brain stem auditory evoked response (BAER) to sound stimuli. Elicitation of the BAER is noninvasive and produces an objective measurement of a subject's auditory function. Basic principles of this technique and normative data are presented in this paper. It was found that the BAER can detect asymptomatic high-frequency hearing losses. The sensitivity of this technique makes it an ideal method for evaluating functional hearing losses. Two illustrations of functional hearing losses are presented. Wave V's threshold, latency and amplitude, along with comparisons between the auditory (subjective) and BAER threshold, are useful parameters when testing for nonorganic hearing disorders. However, this sensitivity to minor hearing losses makes it imperative that all control subjects be established as normal by an audiogram. A mere negative history for hearing disorders is felt by the authors to be an inadequate screening of control subjects.
are probably produced by multiple generators formed by interlacing neuronal pathways. Most of these waves are produced in the brain stem and their elicitation is referred to as the BAER.

These early component waves are very useful in the diagnosis of neurologic and otologic disease. Toxic and metabolic factors, even to the point where coma is produced, have little effect on these waves. The subject's attention to the stimuli has no effect, nor does sleep or bilateral temporoparietal cerebral infarction. Hecox and Galambos even theorize that early components would probably be within normal limits in anencephalic infants.

The middle and late wave components are useful in their own right but beyond the scope of this paper. However, it should be noted that the late components are greatly affected by attention, sleep, drugs and cognitive processes; their elicitation is called the cortical auditory evoked response.

Electrocochleography is a technique similar to BAER but measures responses to sound stimuli using electrodes placed beside the round window. Because the electrodes are closer to the nerve generators, the responses are larger and fewer stimuli need to be averaged. However, tympanostomy must be done and general anesthesia is usually required. Jewett and Williston, Picton et al, and Lev and Sohmer showed that wave I, recorded by scalp electrodes, is identical to wave N1 recorded by round window electrodes. Lev and Sohmer also found that N2 corresponded to wave II. Sohmer and Feinmesser showed that round window potentials could be recorded by external ear electrodes. When recorded by scalp electrodes wave I is small, yet at slow stimulus rates and high dB levels it is usually elicited. Wave V is one of the strongest waves and is time-linked to wave I. Very similar information can thus be obtained by measuring wave V with scalp electrodes rather than waves N1 and N2 with round window electrodes, and an operative procedure is thereby avoided.

If a 500 Hz tone burst is used as a stimulus, two BAER and one frequency-following response (FFR) are produced. The BAER occur as on and off responses elicited by the acoustic transients and overtones found in the rise and fall times of the tone burst. The FFR, as with the cochlear microphonic, is a wave pattern which mimics the waveform of the eliciting stimulus. Various areas of the brain stem produce an FFR. The FFR recorded from the scalp is probably derived from the inferior colliculus. Most researchers use 500 Hz stimuli to elicit this response. The FFR needs further study because of its great potential in providing specific information for low frequencies.

Our clinic has encountered three kinds of situations in which the BAER can be of service. First, the BAER serves as objective evaluation of acoustic function in patients who have a nonorganic hearing loss or in those who have difficulty responding to sound stimuli. An example of the latter is the child who, for uncertain reasons, has not developed speech, and both parents and physicians are not sure if the child is mentally retarded or deaf. Also, children with cerebral palsy or infants with congenital deformities can have their hearing tested by this method. Second, the BAER can also detect occult central
1. AUDITORY EVOKED RESPONSE

I. Acoustic Nerve
II. Cochlear Nucleus
III. Superior Olivary Complex
IV. Nucleus of Lateral Lemnisci
V. Inferior Colliculus
VI. Unknown
VII. Unknown

Fig. 2. Diagram of brain stem auditory evoked response apparatus.

lesions. It is helpful in excluding the existence of an acoustic neuroma and in finding a second occult lesion for the diagnosis of multiple sclerosis. Other occult brain stem pathology may be detected, although in clinical practice these lesions are quite rare. Finally, the BAER is useful in determining brain death. Metabolic coma can mimic brain death by producing a "flat" EEG, but in this condition the BAER may be unaffected. For the above clinical problems, the BAER is a useful tool. This paper is one of three reports which study the BAER's capabilities and limitations in evaluating hearing disorders.

In this first paper, the basic principles and normative data for the BAER are presented. Also, the sensitivity of this technique for detecting mild hearing losses and its utility in testing functional hearing disorders are evaluated.

METHODS AND MATERIALS

The equipment employed in this study was a Nicolet HGA-100 amplifier modified by Nicolet to reduce artifact, a Nicolet CA-1000 signal averager, a click generator, and a pair of shielded headphones. The recording bandwidth was 150 to 3000 Hz.

Click stimuli with a duration of 0.1 msec and an instantaneous rise-fall time were used. The stimuli alternated in polarity on successive stimulations and were presented at a rate of 31/sec at levels starting at 80 dB HL and decreasing by increments of 10 dB until no waves were recorded. Each trial consisted of 2000 click presentations. Only one ear was tested except at the 80 dB level, where both ears were tested. All recordings were repeated and averaged for reliability. Latencies of waves I, III, IV, and V and amplitudes of wave V were recorded. Forty decibels of white noise were used to mask the non-test ear.

Nineteen subjects aged 11 to 40 years were selected. An audiogram was obtained from each subject and no more than a 5 dB loss in any frequency was allowed. All audiograms were plotted by ISO criteria. No subject had a prior history of otologic or neurologic disease. Of these subjects, 15 were pure controls and 4 were tested as "abnormals" with a minimal hearing loss. Two additional patients with a functional hearing loss were tested. Each of

*HL (hearing level) signifies that all decibel levels of equal magnitude had the same acoustic energy. SL (sensation level) denotes that all decibel levels of equal magnitude were of equal sound intensity above the subject's auditory (subjective) click threshold.
these patients had an audiogram and was presented click stimuli at various decibel levels. Thresholds for both click perception (auditory threshold) and for BAER response were determined along with wave V's latency and amplitude. All subjects had a normal otologic exam before the test.

RESULTS

The normative data obtained from the 15 control subjects are presented in Figure 4 and Tables 1, 2, and 3. The means and the standard deviations for latency and amplitude of wave V, elicited by clicks at various decibel levels, are presented in Figure 4. The mean value for latency of wave V (and its standard deviation) increase with decreasing stimulus intensity. The mean and standard deviation for amplitude decrease with lower decibel stimulation.

Table 1 shows that wave V is most stable at lower decibel levels of stimulation. Many subjects, at these levels, produced only wave V; if other waves were present, a wave V was also elicited. Wave II was found only at high decibels of stimulation, and wave IV was often fused to wave V so that its exact latency could not be measured.

The time interval between wave I and wave V (I-V interval) could be record-

ed in all subjects with a click rate of 31/sec by increasing the decibel level to 80. Wave I was not elicited in 2 of the 15 subjects using 70 dB stimuli at a rate of 31/sec. Levels greater than 80 dB were not used on control subjects because they caused discomfort. Table 2 shows the average latencies for the I-V*, I-III and III-V intervals. These intervals did not significantly change when elicited by stimuli of various decibel levels.

The difference in latency of wave V at 80 dB HL at a rate of 31/sec between a subject's right and left ears was found to have a mean of 0.073 msec with a standard deviation of 0.064 msec. Thirteen of the controls had differences between 0.02 msec and 0.096 msec. Two subjects had differences of 0.22 msec and 0.24 msec. Table 1 shows that the standard deviation of wave V elicited by an 80 dB, 31/sec click is 0.121 msec. Thus the intersubject latency difference of wave V is greater than the intrasubject difference. For this reason, some experimenters use the subject's opposite ear as a control when testing for subtle pathology.24

The average threshold for hearing the click, in the 15 control subjects, was 8.33 dB. The threshold for the BAER is

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*Latency of wave V minus latency of wave I = I-V
defined by the authors as the stimulus intensity at which waves are first discernable. As shown in Table 3, no subject had a BAER threshold below the auditory (subjective) hearing threshold. All auditory thresholds were determined under masking conditions. The authors believe that masking tends to distract a subject and to give a falsely elevated auditory threshold, as illustrated by the four subjects in Table 3 with auditory thresholds equal to their BAER thresholds. Under nonmasking conditions, our laboratory has never obtained a BAER threshold that was not at least 10 dB higher than a control subject’s auditory threshold.

The normal BAER threshold is shown in Table 1. Fourteen subjects had thresholds of 20 dB or below; no subject had a threshold less than 10 dB. Only one subject had a threshold of 30 dB. This subject produced a lot of muscle artifact and when she was rerun in a more relaxed state a 20 dB threshold was obtained. The authors use 20 dB as the high normal cutoff for the BAER threshold in a well-relaxed subject.

The latency intensity functions for the two subjects with functional hearing loss are shown in Figures 6 and 7. These subjects had no significant abnormalities of wave V latencies, amplitudes, and thresholds.

**DISCUSSION**

*Derivation of Control Data.* In collecting normative data for the BAER the authors believe it imperative for all subjects to be established as normal with an audiogram. Four subjects in this study were rejected as controls because of a 20 to 30 dB high-frequency hearing loss. All of these four subjects showed latency increases of more than two standard deviations at low decibel levels of stimulation (Fig. 5). Because these subjects were asymptomatic, they would have been included in the control group had audiograms not been obtained. Their inclusion would have resulted in wider standard deviations and decreased sensitivity of the technique because a laboratory cannot distinguish a 10-20 dB loss if subjects with such a loss are part of its control group.

A few experimenters have studied the effect of age on control data and have found latency changes in older subjects with no history of hearing loss.27-28 Because no audiograms were obtained on their experimental subjects, asymptomatic hearing losses might have gone undetected; the increased latencies of the older subjects probably represent no more than the increased incidence of hearing loss with age.

One of those experiments27 presented the auditory stimuli at an equal sound intensity above the subject’s auditory click threshold (SL). That experimental design did not take into consideration
recruitment or the fact that neurosensory losses usually are not equal in all frequencies. Thus the BAER in those subjects may have been produced by a different frequency spectrum than it is in normals, and raising the sound intensity may not necessarily have made those patients comparable to controls.

Obtaining control data in infants is difficult because, below the age of 18 months, latency increases with decreasing age.\textsuperscript{12,13,29} It is felt that this is a maturation phenomenon,\textsuperscript{12,30} possibly related to brain myelination.\textsuperscript{31} Both peripheral and central mechanisms are involved as shown by an increase in wave I latency and the I-V interval, respectively.\textsuperscript{30} In very young and premature infants this latency delay has a higher correlation with age from conception than age from birth.\textsuperscript{12} Not only is the gathering of these data a lengthy process, but their interpretation is difficult because the neonatal ear is not well understood and serous otitis or a collapsing ear canal may be physiologically normal with resolution as the neonate matures. Nevertheless, careful gestational age controls will probably prove very valuable in deriving statements about the patency of the mechanisms of hearing in very young children.

\textbf{Evaluation of Functional Hearing Loss.} Sensitivity of the BAER to minor high-frequency hearing loss makes it a good test for evaluating functional hearing disorders. If a neurologically intact subject has a normal wave V latency, amplitude, and threshold, it is unlikely that a significant high-frequency loss exists. It is very important to elicit wave V's threshold response, because at high decibels of stimulation, latency and amplitude can be normal even when a significant hearing loss is present.\textsuperscript{32} The BAER threshold should also be compared to the auditory (subjective) threshold of the click stimuli. In no control subject (Table 3) and in none of 29 abnormal subjects studied\textsuperscript{32} was the auditory threshold for the click greater than the BAER threshold. However, in functional hearing losses the re-
verse was often found. The two following patients exemplify these points.

*Case 1.* GM (Fig. 6) was a 24-year-old female who had a history of congenital bilateral hearing loss and was being evaluated for dizziness associated with a vague sensation of motion. The audiogram of the patient's right ear showed a 60 dB loss at 8000 Hz and a 40 to 50 dB loss in the other frequencies. The patient's left ear had a similar loss. A Bekesy audiogram revealed a type I tracing but a Stenger test could not be
performed because of the patient's bilateral loss. A Minnesota Multiphasic Personality Inventory suggested a conversion reaction. A BAER was requested to help to rule out an acoustic neuroma. The patient's right ear (GM-R) was found to have near normal wave V latencies with a BAER threshold of 10 dB. The patient's auditory click threshold was 25 dB. As illustrated by subjects with mild hearing losses (Fig. 2), a 60 dB loss at 8000 Hz should cause marked abnormalities. However, the patient's BAER had only insignificant changes. Also, the patient's auditory threshold was 15 dB higher than her BAER threshold. Similar results were obtained with the patient's left ear (GM-L). A diagnosis of functional hearing loss was based on these two observations.

Case 2. RL (Fig. 7) was a 13-year-old male who had a six-year history of a deaf right ear (RL-R) and decreased hearing in his left ear (RL-L). At school the child sat on the right side of the classroom so he could hear his teacher, and was well adjusted to his hearing deficit. The suspicion had been raised that his hearing loss was functional. A Bekesy audiogram was uninterpretable and a Stenger test was positive in only one of three test frequencies. It was finally decided that a true organic loss was present and a trial with a hearing aid was indicated after a BAER confirmed this clinical impression. An audiogram of his left ear showed a 40 to 60 dB loss and he had a 60 dB auditory click threshold. This ear produced normal wave V latencies and amplitudes. It also had a BAER threshold of 30 dB. The patient's right ear had an auditory click threshold of 95 dB, and an audiogram revealed absence of hearing in all the frequencies tested. This ear produced a normal BAER with a BAER threshold of 30 dB. A diagnosis of bilateral functional hearing loss was made.

REFERENCES

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