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STUDIES IN EVOKED POTENTIAL AUDIOMETRY

by

David Richard Stapells

A dissertation submitted to the School of Graduate Studies of the University of Ottawa in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Psychology.

Ottawa, Canada

December 1983

UNIVERSITÉ D'OTTAWA
UNIVERSITY OF OTTAWA

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VITA

David Richard Stapells was born February 11, 1955, amidst the mountains and the sea in Vancouver, B.C., Canada. In 1979, he graduated from Simon Fraser University in Burnaby, B.C., receiving a Bachelor of Arts (Honours) degree in Psychology with a minor in Kinesiology.

He began work on the requirements for the degree of Doctor of Philosophy at the University of Ottawa in January, 1980. His research supervisor was Terence W. Picton, MD, PhD. Throughout his postgraduate studies he was financially supported by the Natural Sciences and Engineering Research Council of Canada.

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ABSTRACT OF THE DISSERTATION

Studies in Evoked Potential Audiometry.

David Richard Stapells

Doctor of Philosophy (Psychology)
University of Ottawa, 1983

Four sets of experiments were performed to evaluate human psychophysical thresholds to brief stimuli and how these behavioral thresholds may be estimated using the auditory evoked potentials.

The normal hearing thresholds for the clicks used to elicit the brainstem auditory evoked potentials were evaluated, and the effects on these thresholds of varying the polarity and symmetry of the click assessed. Threshold decreases 4.5 dB per tenfold change in rate. The average threshold obtained from 40 normal young adults using 100-us square-wave clicks presented through a TDH-49 earphone at 10/s was 36.4 dB peak SPL or 29.9 dB peak equivalent SPL. A root-mean-square measure of the pressure over the initial millisecond -- SPL(1ms) -- provides a more consistent measure of threshold with clicks of differing symmetry than the peak or peak equivalent measures.

The brainstem response to brief tones contains a large vertex-positive component. The morphology of this response changes so that a vertex-negative component becomes prominent when high-pass filter settings above 20 Hz and high rolloff slopes are used. Tones with longer rise-times have greater frequency-specificity, but rise-times longer than 5 ms result in brainstem responses with smaller amplitudes. The brainstem responses to high-intensity stimuli are not frequency-specific, and notched noise masking should be used.

Stimulus presentation rates of 40-45/s result in a 40-Hz sinusoidal response which is about twice the amplitude of the 10 and 60/s responses. The 40/s response shows a linear decrease in amplitude and a linear increase in latency when stimulus intensity is decreased from 90 to 20 dB nHL. This response is recordable to within a few dB of behavioral threshold. High-frequency stimuli result in lower-amplitude responses. Signal averaging and Fourier analysis provide nearly identical amplitude/rate, amplitude/intensity, and latency/intensity functions. Fourier analysis, however, may be the faster and less-expensive method.

Eight evoked potential techniques were evaluated for frequency-specific objective audiometry at 500, 1000, 2000, and 4000 Hz in normal-hearing and hearing-impaired subjects. The tests were the Slow Response, the Transient Middle Latency Response (MLR), the 40-Hz Steady State Potential, and five brainstem response techniques (Derived Responses, Clicks in Notched Noise, unmasked Tone responses, Tones in Notched Noise, and Tones in White Noise). The high noise intensities required to mask clicks may result in small and variable responses and may cause temporary threshold shifts. The ABR/Derived Responses and ABR/Clicks in Notched Noise tests do not therefore appear to be useful for EP audiometry. The Transient Middle Latency Responses are variable and thresholds are difficult to determine and do not appear to be useful for EP audiometry. The results indicate that the auditory brainstem responses to tonal stimuli (masked and unmasked) are the best for audiometry. On average, response thresholds were within 4 - 6 dB of pure tone behavioral thresholds. Noise masking of the tones improves threshold prediction in the presence of steep high-frequency hearing losses.

TABLE OF CONTENTS

INTRODUCTION

This thesis consists of four papers, each representing an attempt to provide some answers to questions in evoked potential audiometry. The format of each paper is that required by the journal in which it has been (or will be) published.

The first paper investigates a topic which is fundamental to the recording of auditory evoked potentials (EP): the behavioral and physical calibration of the acoustic stimuli used in EP audiometry. Published in the Journal of the Acoustical Society of America, this paper provides a normal reference threshold for clicks, and compares techniques for the physical calibration of acoustic stimuli. The studies in this paper also lay down the groundwork for the calibration of normal behavioral thresholds for tonal stimuli. These thresholds are presented in the fourth paper.

The goal of the second paper, published in Ear and Hearing, was to determine the optimal stimulation and recording techniques for brainstem EP audiometry using tonal stimuli. In particular, this paper demonstrates the effects of amplifier filter settings and rolloff slopes, stimulus frequency, stimulus rise-time, and notched noise masking on these responses. The results of these experiments are summarized as a set of recommendations for using this technique.

The third paper, to be published in Ear and Hearing, summarizes experiments investigating the recently-described 40-Hz Steady State Potential. Recent studies suggested that this "new" response might prove to be very useful for EP audiometry. The results of the studies presented in this paper indicate that this steady state potential does show promise for objective audiometry. Furthermore, the results of this paper also indicate that the use of the frequency-based technique of Fourier analysis to record the 40-Hz response may provide information more quickly, more objectively, and less expensively than conventional signal averaging techniques.

The final paper of this thesis presents the results of a study which evaluates the usefulness of eight EP techniques for frequency-specific objective audiometry. The objective was to determine the best test. Each technique was evaluated using the optimal stimulus and recording protocols to provide information within a specified time. All techniques were evaluated in each of ten normal-hearing and ten hearing-impaired subjects. The results presented in this paper clearly delineate the poor EP techniques from the better techniques, and demonstrate their strengths and weaknesses. The paper concludes with a set of recommendations for the practice of evoked potential audiometry.

The four papers in this thesis represent an attempt to answer some of the technical and practical problems of evoked potential audiometry. They are united by the overall goal of providing an accurate and efficient technique for obtaining audiometric information as early as possible in a child's life.

NORMAL HEARING THRESHOLDS FOR CLICKS

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ABSTRACT

This paper evaluates the normal hearing thresholds for clicks and assesses the effects on these thresholds of varying the duration of the listening period and the presentation-rate, polarity and symmetry of the clicks. There were no significant changes in threshold as the listening-period decreased from 2 s to 300 ms. There was, however, a 2.5 dB increase in threshold as the listening-period decreased from 300 to 100 ms. Increasing stimulus presentation-rate from 5 to 80/s decreased threshold 4.5 dB per tenfold change in rate. There were no significant differences in threshold between rarefaction and condensation clicks. The average threshold obtained from 40 normal young adults using 100 μs square-wave clicks presented through a TDH-49 earphone at 10/s was 36.4 dB peak SPL or 29.9 dB peak equivalent SPL. Neither peak SPL nor peak equivalent SPL measurements gave consistent thresholds for clicks with different degrees of symmetry. A root-mean-square measure of the pressure over the initial millisecond - SPL(1ms) - gave a threshold of 25.6 dB. This SPL(1ms) measure of threshold proved to be far more consistent for clicks with different degrees of symmetry than either the peak SPL or the peak equivalent SPL measures.

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INTRODUCTION

Brainstem auditory evoked potentials are extensively used to evaluate human auditory and neurological function (Jerger et al., 1980; Stockard et al., 1980; Glasscock et al., 1981; Rowe, 1981). Most laboratories use broad-band clicks generated by passing short-duration (10-250 µs) electrical pulses through an earphone. There is as yet no standard technique for calibrating the intensity of these stimuli. Both behavioral and acoustical calibrations are presently employed.

There are two methods of obtaining a behavioral calibration of intensity. In the first method stimulus intensity is measured relative to the behavioral threshold of the particular subject being tested ("sensation level" or SL). This is an important measurement but it cannot be used as a standard because it will vary with the ambient noise, the ability of the subject to respond accurately, and the degree of hearing loss. Most laboratories therefore obtain the average threshold of ten normally-hearing young adults (Picton et al., 1977). This second method of behavioral calibration gives a "normal hearing level" or nHL reference. This is similar to the standard reference thresholds ("hearing level" or HL) for pure tones (ISO, 1964; ANSI, 1969) but is specific to the stimulus and to the laboratory. The duration, frequency-spectra and rate of presentation of the stimuli will vary among laboratories.

There are two main disadvantages to nHL calibrations. First, even with identical stimuli nHL thresholds may vary among laboratories because of differences in ambient noise-levels and threshold-estimation procedures, and because of the small numbers of subjects tested. Second, any recalibration of the stimulus (for example, because of changes in the earphone) would require the time consuming re-evaluation of ten normally-hearing subjects.

An acoustic reference for clicks would therefore be very helpful. Unfortunately there is no standard technique for acoustically calibrating a very brief stimulus. Two methods are available for measuring the sound pressure level (SPL) of a transient: "peak SPL" and "peak equivalent SPL" (peSPL). Peak SPL is the intensity of the sound at the peak of the pressure change. It is measured using a sound level meter with a "peak-hold" capability. Peak equivalent SPL is the root-mean-square sound pressure level of a continuous pure tone having the same amplitude as the transient. It is measured by monitoring the output of the sound level meter on an oscilloscope, recording the peak-to-peak amplitude of the transient, adjusting a continuous tone to have an equivalent amplitude, and then measuring the SPL of the continuous tone (Zerlin and Naunton, 1975; Elberling, 1977; Gibson, 1978).[1] When the transient stimulus is symmetrical about the zero-pressure level, peak-equivalent SPL is always 3 dB lower than peak SPL. When the stimulus is asymmetrical, however, the peak equivalent SPL measurement gives a result that is between 3 and 9 dB lower than peak SPL, depending upon the degree of asymmetry (Campbell et al., 1981). Neither the peak nor the peak equivalent SPL measurement accurately evaluates the energy content of the transient. This could be obtained from a root-mean-square measurement of the pressure waveform, but it is difficult to determine over what duration such a measurement should be taken.

The clicks used to evoke brainstem potentials have very short durations and are usually presented at rapid rates (10-100/s). Temporal summation effects can decrease the behavioral threshold for clicks that are presented rapidly or over long periods of time (Zerlin and Naunton, 1975; Yost and Klein, 1979; Weber et al., 1981). It would therefore be necessary to evaluate the role of both the rate of stimulus-presentation and the duration of the listening-period when obtaining an acoustic calibration for the normal behavioral threshold for clicks.

This paper presents the results of several experiments investigating the effects on behavioral threshold of varying the polarity, presentation rate and symmetry of the clicks, and the duration of the listening-period. The goal of these experiments was to obtain an appropriate acoustic calibration of the normal hearing threshold for clicks.

METHODS

A. Subjects

Twenty-two male and twenty-three female subjects, aged between 18 and 38 years, participated in one or more of the experiments. Pure tone thresholds were obtained using the method of limits with 5 dB steps. For each subject the average pure tone threshold across the freqencies 500, 1000, 2000, and 4000 Hz was less than 15 dB HL. The threshold at any one of these frequencies was never greater than 20 dB HL (ANSI,1969). The mean threshold over all frequencies and all subjects was 3.3 dB HL, with a standard deviation of 6.0 dB.

B. Stimuli

All stimuli were presented through a TDH-49 earphone mounted in a MX41/AR cushion. The stimuli were calibrated daily using a Brüel and Kjaer 2209 sound level meter and NBS 9-A earphone coupler (Brüel and Kjaer Type 4152(DB 0909) with 1" microphone Type 4144). The stimulus waveform was also amplified on a Brüel and Kjaer Type 2619 preamplifier and digitized on a Tracor Northern TN-1500 signal analyzer. The root-mean-square SPL over the initial millisecond of the stimulus - SPL(1ms) - was calculated as a measurement of the peak energy of the stimulus. The one millisecond period was chosen arbitrarily. The frequency spectra of the stimuli were also calculated and plotted using logarithmic axes.

The 100 μs clicks used in the first three experiments were produced by passing 100 μs square-wave pulses through the TDH-49 earphone. These pulses were generated by a Tracor Northern TN-3000 Clinical Evoked Potential System, amplified using a Bryston 2B audio amplifier, and attenuated using Wavetek 5010 and 5070 attenuators. The intensity measurements using this system were accurate to within 0.5 dB. The acoustic waveforms and frequency spectra of these clicks are shown in Figure 1. No differences were noted between condensation and rarefaction clicks.

The stimuli used for the fourth experiment were a 2 kHz single-cycle sine wave ("2 kHz-symmetrical click") and a 2 kHz single-cycle offset cosine-wave ("2 kHz-asymmetrical click"). The single-cycle cosine was offset by an amount equal to its peak amplitude to eliminate the sharp initial and final transients which would otherwise be present. The acoustic waveforms and frequency-spectra of these stimuli are shown in Figure 2. There were no differences between condensation and rarefaction stimuli although the symmetrical and asymmetrical stimuli were quite distinct. The 2 kHz-asymmetrical stimulus is similar to that used by Salomon and Elberling (1971).

The testing took place in a single-walled IAC sound-attenuated chamber. The sound pressure level in the room was measured as 55 dB SPL using a bandpass of 20 Hz - 20 kHz, and 21 dB SPL using the A-weighting network. The octave-intensities of the background noise at

250, 500, 1000, 2000, and 4000 Hz were 11, 7, 8, 8.5, and 9 dB SPL respectively.

C. Experimental procedures

For all experiments there was a 10-minute practice session prior to threshold evaluation. During this time the subject became familiar with the experimental paradigm, and the experimenter obtained an approximate threshold using the method of limits with 2 dB steps.

In the first experiment, the subjects listened at ten intensities spanning in 2 dB steps an 18 dB range centered at an approximate normal threshold which had been obtained in a pilot study. The clicks were presented at a rate of 10/s. A "listen" light lasting two seconds signaled that there was a 50% probability of clicks being present. After two seconds a "respond" light came on and the subject made a yes/no button press response. Responses to ten stimulus-present and ten stimulus-absent trials were obtained at each of the ten intensities for both condensation and rarefaction 100 μs clicks.

Five changes were made in this paradigm for the second, third, and fourth experiments. First, a 500 ms "warning" light began one second prior to the listening-period. Second, a one second listening-period replaced the two second listening-period during experiments 2 and 4. Third, four button-press confidence-ratings were used instead of the yes/no response. Fourth, fewer stimulus intensities were used. Responses were evaluated at 4 - 8 levels spanning the approximate threshold obtained for each subject during the practice sessions.

These levels were separated by 2 dB for Experiments 2 and 3, and by 1 dB for Experiment 4. Fifth, the number of trials at each intensity was increased to 30 for Experiments 2 and 3, and to 40 for Experiment 4.

D. Data-analysis

In the first experiment the proportion of correct detections at each intensity was adjusted to compensate for guessing using the formula (Gescheider, 1976):

$$P(\text{correct detections}) = \frac{P(\text{yes}\,|\,\text{stimulus present}) - P(\text{yes}\,|\,\text{stimulus absent})}{1 - P(\text{yes}\,|\,\text{stimulus absent})}$$

Thresholds were obtained by interpolating to the intensity at which there were 50% correct detections.

In the next three experiments a receiver operating characteristic (ROC) curve was plotted on the basis of the three criteria separating the four different confidence-ratings (Green and Swets, 1966; Gescheider, 1976). The area under the ROC curve was calculated for each intensity. This gave a measure of signal detectability that was distribution-free and independent of response bias. Thresholds were obtained by interpolating to the intensity where the area under the ROC curve was 75%. This was roughly equivalent to the adjusted 50% correct detection level used in the first experiment.

The data were analyzed using Student t-tests, Pearson product-moment correlation coefficients, repeated-measures analyses of variance, and Tukey HSD (1953) post hoc testing procedures. Results were considered significant at $p<0.01$.

RESULTS

Experiment 1: Normal thresholds for 100 μs clicks

Twenty male (mean age 24.3 yrs) and twenty female (mean age 23.8 yrs) subjects participated in this study. One ear was tested for each subject using condensation and rarefaction 100 μs clicks. The subjects were balanced across age, sex and ear. The average thresholds are shown in Tables I and II. Figure 3 shows the range of thresholds as measured in peak SPL. There were no significant differences in threshold between males and females ($t = 0.24$, $df = 78$, $p>0.8$), between right and left ears ($t = 0.45$, $df = 78$, $p>0.6$), or between condensation and rarefaction clicks ($t = 0.45$, $df = 39$, $p>0.6$). There was no significant correlation between age and threshold ($r = -0.1$, $p>0.25$). The overall average threshold obtained was 36.4 dB peak SPL, 29.9 dB peak equivalent SPL, or 25.6 dB SPL(1ms). The standard deviation was 2.7 dB, with a range of 29 to 45 dB peak SPL.

Experiment 2: The rate of stimulus-presentation

Five male and five female subjects participated in this experiment. Rarefaction(100 μs) clicks were presented at rates of 5, 10, 20, 40, and 80/s. The order of selecting rate and intensity was randomized. There was a significant effect of rate on thresholds ($F = 19.0$, df = 4,36 ; $p<0.001$). The average data are plotted in Figure 4. A logarithmic regression line fitted to the data showed a slope of 4.53 dB per tenfold change in click-presentation rate ($r = -0.48$, $p<0.001$). The average threshold obtained at 10/s was 36.2 dB peak SPL with a standard deviation of 3.95 dB.

Experiment 3: Duration of listening-period

Four male and six female subjects participated in this experiment. Rarefaction(100 µs) clicks were presented at a rate of 40/s. The listening-period was set at 0.1, 0.2, 0.3, 0.5, 1.0, and 2.0 seconds. There was a significant effect of increasing listening-period duration on the threshold ($F = 12.85$, df = 5, 45; $p<0.001$). The threshold improved by 2.5 dB as the duration increased from 0.1 to 0.3 s. The threshold at 0.1 s was significantly elevated compared to the thresholds obtained with durations of 0.3 s or longer (Tukey $HSD_{0.01}$ = 2.4 dB). The average data are plotted in Figure 5.

Experiment 4: Click symmetry

The symmetrical and asymetrical 2 kHz clicks used in this experiment differed in their intensity-measurements according to peak SPL or peak equivalent SPL. The difference between the two SPL measurements for the asymmetrical stimulus was 8.1 dB while for the symmetrical stimulus the difference was 2.9 dB (peak SPL greater in both cases). Comparison of the thresholds for these stimuli could therefore demonstrate whether peak SPL or peak equivalent SPL was the more consistent measurement for clicks of different morphologies. Five male and five female subjects participated in the experiment. Four separate stimulus conditions were used: asymmetrical-rarefaction, asymmetrical-condensation, symmetrical-rarefaction, and symmetrical-condensation, the polarity of the symmetrical stimuli being determined by their initial deflection. The stimulus conditions were presented in balanced order.

The average thresholds for the 2 kHz stimuli are shown in Table II, with the mean thresholds for the 100 μs click stimulus from Experiment 1 included for comparison. The thresholds as measured in peak SPL were significantly different between the symmetrical and asymmetrical stimuli ($F = 12.4$, df = 1,9; $p<0.01$), as were the thresholds measured in peak equivalent SPL ($F = 14.9$, df = 1,9; $p<0.005$). There were no significant differences between the SPL(1ms) measurements ($F = 0.06$, df = 1,9; $p>0.25$). Furthermore, there were no significant differences between rarefaction and condensation stimuli $F = 0.03$, df = 1,9; $p>0.25$).

DISCUSSION

We obtained a mean threshold of 36.4 dB peak SPL or 29.9 dB peak equivalent SPL for 100 μs square-wave clicks presented at a rate of 10/s. This is similar to the thresholds reported by others. Table III presents published threshold-data and laboratory-thresholds obtained from several colleagues. There is a range of approximately 10 dB in these reported thresholds. Some of this may result from different stimulus-presentation parameters or levels of ambient noise. Our results were quite similar whether thresholds were obtained using classical psychophysical methods (Experiment 1) or measures of signal detectability (Experiment 2). The thresholds therefore appear to be quite reliable. The absence of any threshold-difference between rarefaction and condensation clicks replicates the findings of Flanagan (1961) who reported a threshold of 30 dB peak SPL for 100 μs clicks of different polarities when presented binaurally at rates from 20 to 102/s.

Increasing the rate of stimulus presentation from 5/s to 80/s decreased the threshold level by about 5 dB. Perceptual processes integrate acoustic energy over several hundred milliseconds (Zwislocki, 1969; Pedersen and Salomon, 1977). Increasing the rate at which brief stimuli are presented probably invokes this temporal summation in a similar manner to increasing the duration of a continuous sound

(Zwicker, 1975). There are, however, some differences between the summation processes for the two types of stimuli. Experiment 2 demonstrated a smaller summation effect (4.5 dB per tenfold increase in rate per second) for clicks than has been reported for continuous pure tones (8-10 dB per tenfold increase in duration). Other studies using brief tonal stimuli have reported effects of stimulus presentation rate that are similar to the present study (Zerlin and Naunton, 1975; Picton et al., 1979; Yost and Klein, 1979). The smaller summation effect may be related to the wide frequency-content of brief stimuli, Zwicker (1975) and Garner (1947) having reported smaller temporal summation effects for broad-band stimuli. The actual high-frequency content of the stimulus may also play a part since there is less temporal summation at higher frequencies for pure tones (Watson and Gengel, 1969; Pedersen and Salomon, 1977; Chung, 1981) and for third-octave clicks (Zerlin and Naunton, 1975). Zwislocki (1960, Figure 9) reported a 10 dB summation effect per tenfold change in the presentation rate of 0.5 ms clicks. Flanagan (1961), on the other hand, reported very little change in the threshold for 100 μs clicks presented at rates increasing from 20 to 102/s. It is possible that these differences may be related to the different frequency spectra of the different stimuli, the 500 μs pulse of Zwislocki containing relatively more low-frequency energy.

We observed a 2.5 dB decrease in threshold as the listening-period was increased from 100 ms to 300 ms. This indicates a temporal summation period within these limits, comparable to the 200 ms period reported by others (Zwislocki, 1969; Zwicker, 1975). The data shown in our Figure 5 are quite similar to those plotted by Zwislocki (1960, Figure 7) for 100/s clicks with durations of 0.2 - 2.0 ms. Both sets of data show a decrease in threshold of about 5 dB as the listening duration increased from 100 ms to 1 second.

Our results concerning click-symmetry illustrate some of the problems associated with the measurement of the intensity of brief broad-band stimuli. Neither the peak SPL nor the peak equivalent SPL measurements gave consistent thresholds for clicks with different degrees of symmetry. In contrast, the SPL(1ms) measurement appears to provide a reasonable evaluation of the energy of the click during its period of peak excursion, and is less affected by the stimulus waveform than the peak SPL and peSPL measurements. The SPL(1ms) measure gives consistent thresholds for the 2 kHz clicks at different degrees of symmetry, and the threshold obtained for these clicks - 24.8 dB SPL(1ms) - is also very similar to the threshold obtained for the 100 μs square-wave click when this intensity measure is used (25.6 dB). The selection of the 1 ms period is, however, somewhat arbitrary, and some difficulty with the SPL(1ms) measure might be encountered with very brief signals that have most of their energy in the high frequencies , or signals with a wave form lasting longer than one millisecond. Further studies involving a variety of stimuli will therefore be required to assess the usefulness of this measure.

The stimuli used in different laboratories will certainly differ in their acoustic morphology. The click produced by Özdamar and Stein (1981) has a waveform and frequency-spectrum which is similar to our 2 kHz-symmetrical stimulus, whereas that produced by Elberling (1977) is more similar to our 2 kHz-asymmetrical stimulus. Different earphones vary a great deal on how symmetrical a click they produce even when activated by the same square-wave pulse (Weber et al., 1981). The asymmetrical stimuli have a relatively flat frequency-spectrum in the response-region of the earphone whereas symmetrical stimuli have a spectrum which falls off toward the lower frequencies. The peak SPL thresholds we obtained in our first experiment are therefore appropriate only to clicks with a relatively flat spectrum (i.e. within 5 dB) over the frequency range 500 - 4000 Hz .

Another problem with the calibration of the intensity of a brief transient is the choice of earphone-coupler. We used an NBS 9-A , 6 cc coupler (ANSI,1973), the Brüel and Kjaer Type 4152(DB 0909) artificial ear with a 1" microphone (Brüel and Kjaer Type 4144). The fact that the frequency-response of this microphone does not reach beyond 8 kHz is probably not significant because the frequency-response of the TDH-49 earphone also does not extend significantly beyond 8 kHz. The use of different coupling devices can give different measurements for the morphology and the intensity of an acoustic stimulus produced by the same earphone. These differences may be as large as 5 dB (Elberling, personal communication). Similar acoustic differences could be expected between different human ears, and optimally one would like to measure the click waveform in the external auditory meatus near the eardrum. At present, however, such a measure is not readily feasible for clinical use.

In order for the perception of a stimulus to occur it is necessary for neural responses to be initiated. The threshold for initiating neural responses must therefore be at the lowest perceptual threshold one could obtain with increasing rates of stimulus presentation. Since the stimuli have a duration of 1-2 ms, this would probably be 6-9 dB less than the threshold at 10/s. In our experience (Campbell et al., 1981) brainstem responses are often not identifiable at intensities below 60 dB peak SPL. The fact that brainstem responses are not recordable at lower levels is not caused by an absence of neural response. It could be caused by the lack of consistent timing ('latency-jitter') in the response and/or the presence of unaveraged background noise in the recording. Because of the difficulty in extrapolating to an absolute neural threshold, we therefore feel that nHL thresholds should be calibrated at one particular rate. Since a rate of 10/s is commonly used in recording brainstem responses we feel that nHL calibrations should be determined at this rate.

How then should clicks be calibrated for use in brainstem evoked potential studies? We recommend that the clicks be broad-band and have a relatively flat spectrum from 500 to 4000 Hz. The normal hearing threshold for such clicks presented at a rate of 10/s is 36.4 dB peak SPL, 29.9 dB peak equivalent SPL, or 25.6 dB SPL(1ms). Between presentation rates of 5 and 80/s the threshold decreases 4.5 dB per tenfold change in rate.

FOOTNOTES

[1] Unfortunately there is some controversy in the literature as to whether the continuous tone should be adjusted to equal the transient on the basis of its peak-to-peak amplitude (Zerlin and Naunton, 1975) or its peak amplitude (Arlinger,1981).

ACKNOWLEDGMENTS

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TABLE I 100 μs CLICK THRESHOLDS

		Left Ear		Right Ear	
		Rarefaction (dB)	Condensation (dB)	Rarefaction (dB)	Condensation (dB)
Male	mean	36.9	37.6	35.4	35.9
	s.d.	3.5	2.9	1.5	1.3
Female	mean	36.2	35.3	36.8	36.9
	s.d.	3.2	2.4	3.6	2.6

Clicks presented at 10/s .

Measurements in peak SPL (pe SPL is 6.5 dB less; SPL(1ms) is 10.8 dB less).

TABLE II 2 kHz CLICK THRESHOLDS

Threshold Measure (dB)	2 kHz CLICKS Asymmetrical Rare.	Cond.	Symmetrical Rare.	Cond.	100 μs CLICKS
peak SPL	32.6	32.2	29.8	30.1	36.4
peak equivalent SPL	24.5	24.1	26.9	27.2	29.9
SPL(1ms)	24.8	24.4	24.9	25.2	25.6
standard deviation	3.0	3.0	3.9	3.7	2.7

2 kHz click data from fourth experiment. 100 μs click data from first experiment. All stimuli presented at 10/s .

TABLE III LABORATORY THRESHOLDS

ORIGIN	STIMULUS	RATE (/s)	peakSPL (dB)	peSPL (dB)
Published				
Campbell et al.(1981)	100 µs click	10	40.0	34.0
Elberling(1977)	2 kHz half-sine	10	-	28.5
Özdamar & Stein(1981)	100 µs click	20	-	32.0
Selters & Brackmann(1977)	160 µs click	20	38.0	-
Personal communication				
Berlin(New Orleans)	100 µs click	17.7	43.0	-
Davis(Saint Louis)	2 kHz sq.wave	25	29.5	-
Don(Los Angeles)	160 µs click	13	-	32.2
Martin(Houston)	24 µs click	8	-	34.9
Onishi(Yokohama,Japan)	4 kHz(1 cycle)	10	-	36.5
Present Study	100 µs click	10	36.4	29.9

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FIGURE LEGENDS

FIG. 1. 100 µs clicks. The clicks were produced by passing 100 µs square waves through a TDH-49 earphone. Acoustic waveforms (left) and spectra (right) of the clicks used in Experiments 1, 2, and 3.

FIG. 2. 2 kHz clicks. Acoustic waveforms of the 2kHz-asymmetrical (top left) and the 2kHz-symmetrical (bottom left) clicks used in Experiment 4 and their spectra (right).

FIG. 3. Behavioral thresholds for 100 µs clicks presented at 10/s. Thresholds for rarefaction and condensation clicks in dB peak SPL from 40 subjects (Experiment 1). Mean threshold = 36.4 dB peak SPL (29.9 dB peSPL; 25.6 dB SPL(1ms)). Standard deviation = 2.7 dB.

FIG. 4. Effects of stimulus presentation rate on the threshold for 100 µs rarefaction-clicks. A one-second listening-period was used. Results are the average of data from 10 subjects.

FIG. 5. Effects of the duration of the listening-period on the threshold for 100 µs rarefaction-clicks. Presentation rate was 40/s. Results are the average of data from 10 subjects.

Figure 1

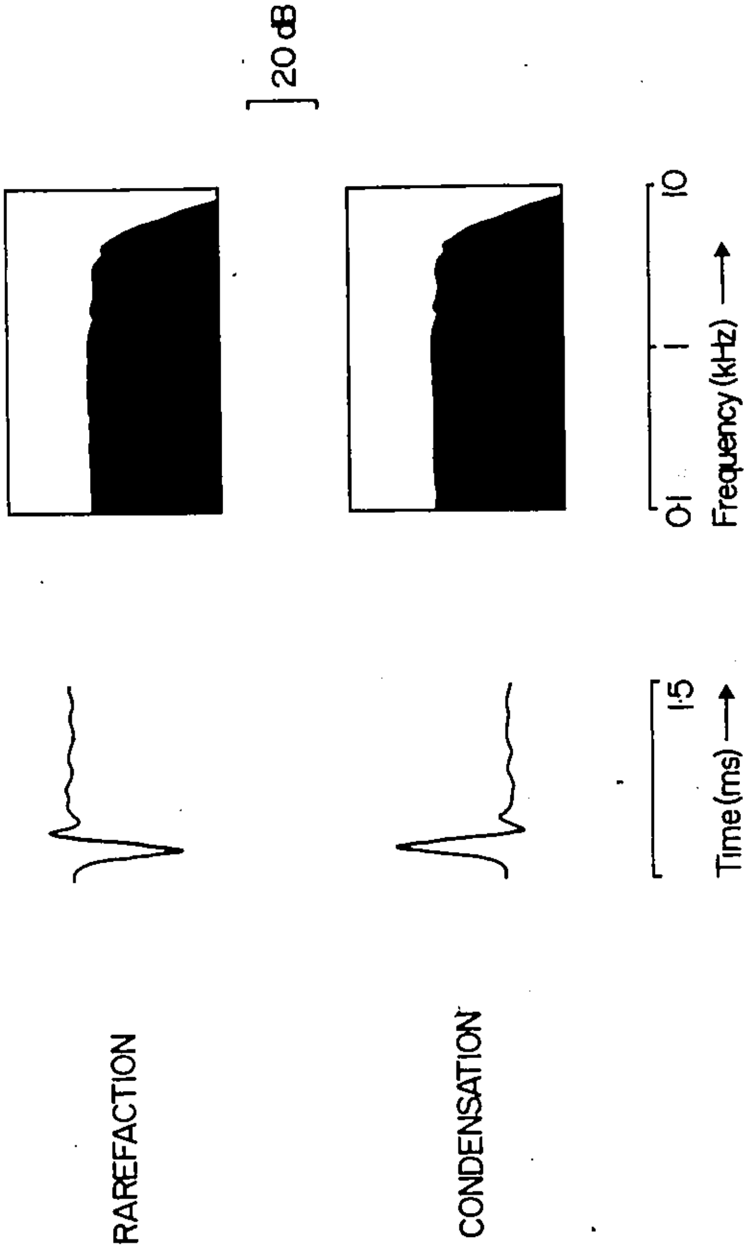

20 dB
RAREFACTION
CONDENSATION
0.1
1
10
Frequency (kHz)
1.5
Time (ms)

Figure 2

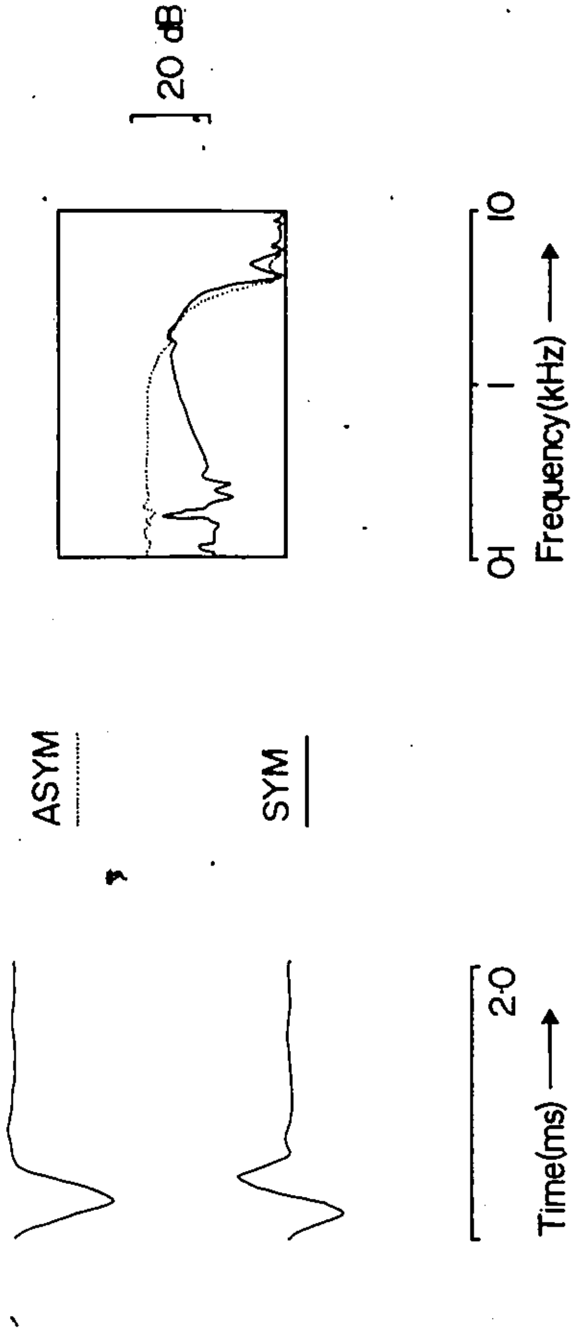


Figure 3

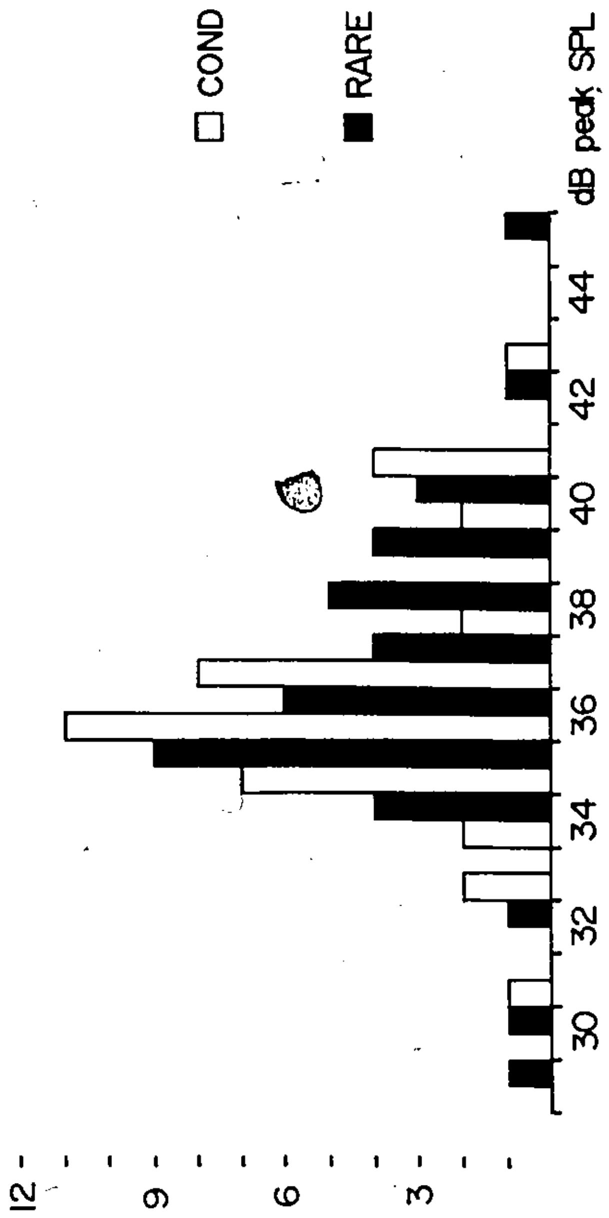


Figure 4

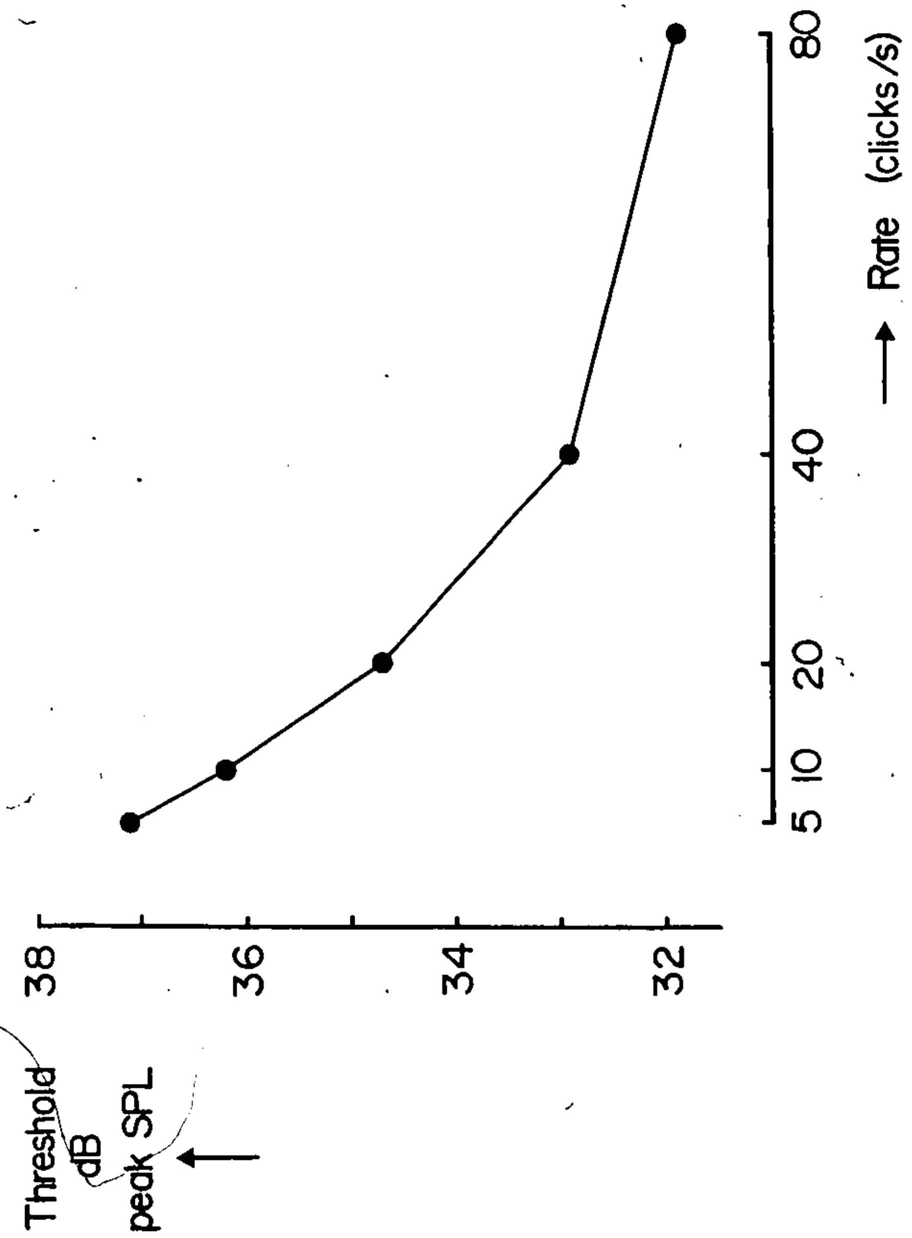
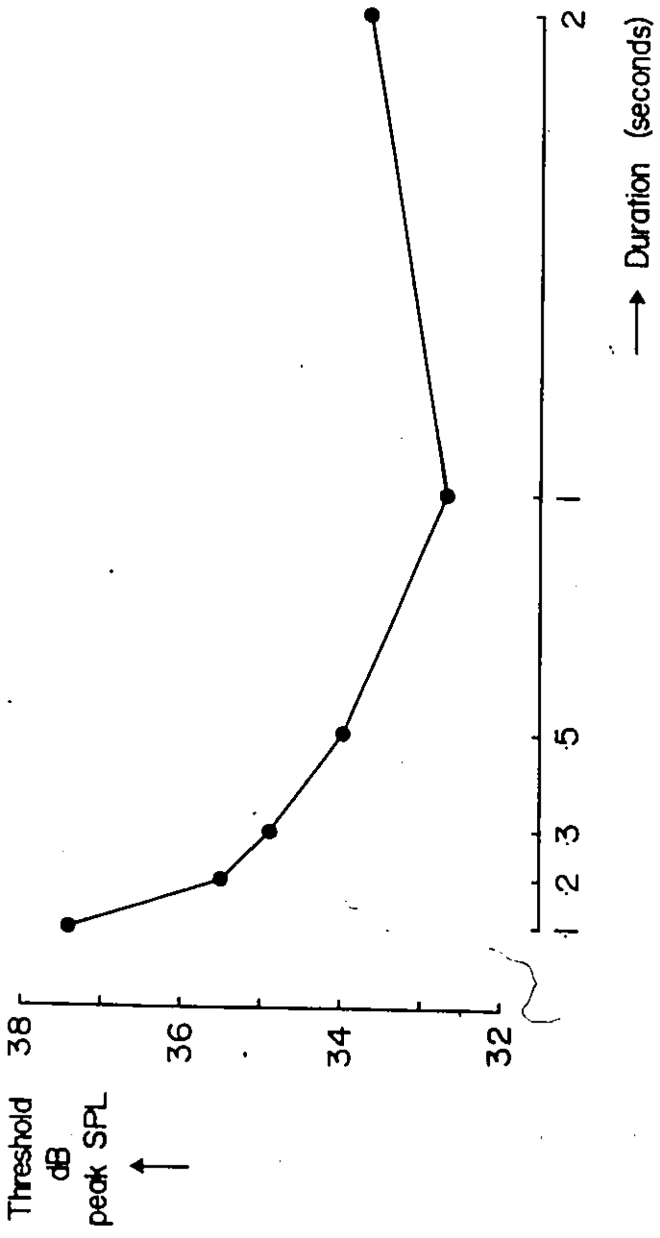


Figure 5



Ear and Hearing

Technical aspects of brainstem evoked potential audiometry using tones

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ABSTRACT

The brainstem response to brief tones contains a large vertex-positive component. If filter settings of greater than 20 Hz are used, particularly with high rolloff slopes, the morphology of the response changes so that a vertex-negative wave becomes the most prominent component of the response. The amplitude of the response is unaffected by stimulus presentation rates of up to 35/s. Tones with longer rise-times have greater frequency specificity, but at rise-times of greater than 5 ms the brainstem response becomes very small. At high intensities, regardless of the rise-time, the response to tones is not completely frequency-specific and notched noise masking should be used to obtain frequency-specific responses.

INTRODUCTION

The brainstem potentials evoked by click stimuli can provide a reliable and objective assessment of auditory function (4, 12, 25, 34). It is difficult, however, to determine frequency-specific thresholds using wide-band click stimuli. Several techniques have therefore been proposed for obtaining a full-frequency audiogram from brainstem recordings.

The "derived response" technique requires recording the brainstem responses to clicks presented in high-pass masking noise. Sequential subtraction of the responses recorded using different cutoff settings for the high-pass noise gives derived responses to the frequencies between the cutoff settings. These derived responses have been recorded from the human brainstem (9, 19, 20) and have been used to provide frequency-specific threshold information in patients with hearing impairment (10). This technique is accurate and reliable; it is, however, more complex and time-consuming than simple evoked potential recording.

A simpler approach is to record brainstem responses to frequency-specific stimuli - filtered clicks, tonepips and brief tonebursts. Initially, brainstem responses were recorded using stimuli with frequencies of greater than 1 or 2 Hz (18, 24, 31, 32). Responses to lower frequency stimuli (26) appeared to be either too small to recognize easily at low intensities, or mediated by the high-frequency region of the cochlea (7). The use of wider amplifier bandpasses extending below 100 Hz (28) made the response to low-frequency tones more easily recognizable. Recently, several researchers have reported brainstem responses to brief tones with frequencies as low as 250 or 500 Hz (2, 5, 8, 14, 16, 27, 33). There is some controversy in the literature, however, about the nature of the response recorded to low frequency tones. Most authors report a prominent vertex-positive wave - apparently equivalent to the V component of the click response occurring with longer latency because of both the travelling-wave delay to the low-frequency regions of the cochlea and the longer rise-time of the stimulus. Davis and Hirsh (8), however, using a 40 Hz 24 dB/octave high-pass filter, find the main component of the response to be a vertex-negative wave that they call SN_{10}. One reason for this difference could be the particular filter settings used by Davis and Hirsh (22, 28). Another cause could be the overlapping of the brainstem response with the middle-latency response to the preceding tone when rapid rates (33/s) of stimulus presentation are used.

Tones of short duration and/or rapid rise-time contain acoustic energy at frequencies away from their nominal frequency. The shorter the duration or the rise-time of the tone the greater the spread of acoustic energy. Spectral analysis of the acoustic waveform can be used to evaluate the frequency-specificity of a brief tone. Two factors, however, make it difficult to rely on such a spectrum as an indicator of the frequency-specificity of the response evoked by that tone. First, there may be further distortion of the stimulus during transmission through the middle ear - particularly if the intensity is high. Second, the response may be evoked only by the onset of the tone and not by the entire tone that is evaluated in the acoustic spectrum. The spread of energy in brief tones can result in spuriously low thresholds being obtained during evoked potential audiometry. In patients with large differences in threshold between different frequencies a brainstem response may be evoked not by the energy in the tone at its nominal frequency but by the energy in the skirts of the spectrum (21, 23). Because of this problem Picton and his colleagues (23) proposed the use of "notched noise" masking to limit the tone-response to a specific area of the cochlea. This technique yielded more accurate threshold information than the use of tones alone. However, the tones used in this study were quite brief - 1 ms rise-time, 1 ms plateau, and 1 ms fall-time. It is therefore possible that tones of longer rise-time - and therefore of greater acoustic frequency-specificity - may evoke responses of sufficient frequency-specificity to render the notched noise unnecessary.

This paper presents the results of several experiments designed to investigate various technical aspects of recording the auditory brainstem response to tones. The effects of amplifier high-pass filter setting and rolloff slope, stimulus presentation rate, reference electrode location, stimulus intensity, stimulus frequency, stimulus rise-time and notched noise are all investigated. The general goal of the experiments was to determine the optimal stimulation and recording techniques for brainstem evoked potential audiometry using tones.

METHODOLOGY

This section describes the methodology common to all of the experiments. The specific details of each experimental design are included for clarity in the description of the results.

Recordings were made from 11 volunteer subjects aged between 22 and 30 years. Recordings were taken from 8 subjects in each experiment. Most of the subjects participated in all 6 experiments. Five subjects were female. All subjects had no history of hearing difficulty and all had normal hearing ($<$15 dB ISO) between 500 and 4000 Hz. During the recording the subject sat quietly in a reclining chair and either read or fell asleep.

The 500 Hz tones employed in the first 4 experiments had a linear rise-time of 5 ms, a plateau duration of 0 ms and a fall-time of 5 ms. This stimulus was produced by gating the output of a Tektronix FG501 function generator with a Grason-Stadler 1287B electronic switch. The tone was timed, amplified and attenuated on other Grason-Stadler modules and presented to the subject's left ear through a TDH-49 earphone. The onset phase of the tone was random.

The auditory stimuli employed in Experiments 5 and 6 were generated by a Tracor Northern TN-3000 clinical averaging system. Tones with linear rise-times of 1, 2, 5 and 8 ms, equal fall-times and plateau durations of 0.01 ms were used at frequencies of 500, 1000, 2000 and 4000 Hz with alternating onset polarity. The noise employed in Experiment 6 was generated by the TN-3000 system and filtered using a Krohn-Hite 3343 filter set in band-reject mode using a 2 octave range centered on the tone frequency with 48 dB attenuation at that frequency. The tone and filtered noise were mixed, amplified and attenuated for presentation to the subject's left ear using a TDH-49 earphone.

The stimuli were calibrated using a Brüel and Kjaer 2209 sound level meter with a 4144 microphone and a 4152 artificial ear. The frequency spectra of the TN-3000 stimuli were evaluated using a 4144 microphone with a 2619 preamplifier to measure the acoustic stimulus and a laboratory-programmed Tracor Northern TN-1500 signal analyzer to perform the frequency analysis. Power spectral density plots for the 500 and 2000 Hz tones at an intensity of 115 dB peak SPL are shown in Figure 1.

..................Insert Figure 1 about here..................

Electroencephalographic signals in all 6 experiments were recorded from the scalp using Grass gold-plated electrodes connected to the scalp using Beckman saline gel and collodion-impregnated gauze. Interelectrode impedances were kept below 3000 Ohms. In Experiments 1 to 4 electrodes were applied at the vertex, left mid-mastoid and left low-mastoid (2-3 cm below the mid-mastoid). In Experiments 5 and 6 only one reference electrode was placed on the left low-mastoid. All 6 experiments employed a ground electrode on the right mastoid.

In Experiments 1 to 4 the electroencephalographic signals were amplified on Beckman R-611 polygraph amplifiers with a bandpass (-3 dB) of 0.16 to 1900 Hz and a rolloff of 6 dB/octave. Responses to approximately 5000 individual stimuli in each of the experimental conditions were stored on FM-tape (Hewlett-Packard 3960, bandpass of DC-5000 Hz) for later off-line averaging using the TN-3000 system (bandpass 0.1 - 10,000 Hz). The electroencephalogram in experiments 5 and 6 was amplified using the TN-3007 preamplifier and the TN-3000 system with a bandpass of 10-3000 Hz and 12 dB/octave rolloff slopes.

The tape-recorded electroencephalogram from the first four experiments was played back using different high-pass filter settings and rolloff rates. Low-pass filtering in these experiments was always set at 3000 Hz-48 dB/octave using the Krohn-Hite 3343 filter. High-pass filtering was accomplished using 1, 2 or 4 Tektronix AM502 amplifiers in series with unity gain. These amplifiers were modified to provide the necessary filter settings for the experiments. Since rolloff slopes add when the filters are placed in series, this arrangement allowed for high-pass filter rolloff slopes of 6, 12 and 24 dB/octave. Small decreases in the filter cutoff frequencies as measured using the -3 dB points also occurred at the 12 and 24 dB/octave settings, but these changes (1/4 and 9/24 octaves) were not considered significant to the experimental design. The Krohn-Hite 3343 filter was used to give the 48 dB/octave rolloff slope used in Experiment 1.

Averaging was carried out for between 1000 and 4000 responses using the TN-3000 system. Averaging was done off the tape recorded data for the first four experiments and on-line for the last two experiments. Trials containing amplitudes of greater than ±20 µV were automatically rejected from averaging except in Experiment 3 where no artifact rejection was employed. The average evoked potential waveforms were stored on diskettes using the TN-1007 disk drive for later plotting and peak measurements.

The maximum positive peak occurring between 6 and 16 ms after the tone onset was recorded as the V component of the brainstem response. If the peak was in the form of a plateau the latency was taken at the center and the amplitude was measured to the maximum point on the plateau. The most prominent negative peak occurring within 7 ms after the wave V peak-latency was identified as component V'. If no distinct negative peak occurred, the maximum negativity within this interval was recorded. Amplitude measurements were taken relative to baseline for each peak V and V', and the V-V' peak-to-peak amplitude was calculated. Unless otherwise noted, "amplitude" represents the V-V' peak-to-peak amplitude. These measurements were evaluated using a repeated-measures analysis of variance and appropriate post hoc testing procedures. Results were considered as significant at $p<0.01$.

RESULTS AND DISCUSSION

Experiment 1 - High-pass Filter Settings

This experiment was designed to evaluate the effects of different amplifier high-pass filter settings and rolloff slopes on the brainstem responses to 110 dB peak SPL 500 Hz tones presented at a rate of 10/s. The evoked potentials recorded betwen the vertex and mid-mastoid electrodes were filtered prior to averaging through 1, 2 or 4 Tektronix amplifier or through the Krohn-Hite filter to obtain rolloff slopes of 6, 12, 24 and 48 dB/octave. Filter settings of 10, 20, 40, 70 and 100 Hz were investigated. The low-pass filter was set at 3000 Hz (48 dB/octave) for all conditions.

The brainstem responses from a typical subject are shown in Figure 2 and the average latency and amplitude data for all 8 subjects are plotted in Figure 3. The latency of wave V and the V-V' amplitude both decreased as either the cutoff setting or the rolloff slope of the high-pass filter increased. With the 6 dB/octave filters the average wave V latency decreased from 8.57 to 8.40 ms from 10 Hz to 100 Hz with a corresponding amplitude decrease of 0.41 to 0.30 µV. With the 48 dB/octave filters the changes were somewhat greater - from 8.46 to 8.11 ms for the latency and from 0.44 to 0.10 µV fot the amplitude. The latency of the V' component also decreased with increasing filter cutoff setting or rolloff slope. These decreases were much greater than those seen with wave V. The average latency of V' decreased from 13.52 to 9.43 ms as the filter settings changed from 10 Hz-6 dB/octave to 100 Hz-48 dB/octave. At 40 Hz-24 dB/octave the V' latency was 11.53 ms.

.............Insert Figures 2 and 3 about here..................

The morphology of the response was greatly altered at the higher filter settings, particularly when higher rolloff slopes were also used. The vertex-negative V' wave was especially prominent at the 40 Hz-24 dB/octave filter setting. This "prominence" of the V' component was evaluated by calculating the V'/V amplitude ratio. This ratio was greater than one at filter settings of 100 Hz using rolloff slopes of 12 dB/octave or more, at 70 and 40 Hz using rolloff slopes of 24 dB/octave or more, and at 20 Hz using rolloff slopes of 48 dB/octave. The most prominent V' waves assessed by this ratio were recorded at filter settings of 20 Hz-48 dB/octave and 40 Hz-24 dB/octave.

These results indicate that the effects of filtering on the brainstem evoked potentials are complex. The brainstem evoked potential to clicks of moderate intensity contains its major power in the 50 to 250 Hz region and at lower intensities the main power shifts toward the lower frequencies of this range (11). Any high-pass filtering in this frequency range will change the amplitude of the response. If the filtering is performed using analog filters there will also be phase changes that will alter the morphology and latency of the response (1,3). The phase changes can be prevented if digital filtering is used but this requires more computationsl power than is usually available for clinical testing. Suzuki and Horiuchi (28) have pointed out that the brainstem response to 500 Hz tones is particularly susceptible to high-pass filter settings of 50 Hz or more using 6 dB/octave rolloff slopes. Using higher rolloff slopes marked alterations in response morphology can be seen. Using a 50 Hz cutoff with a rolloff slope of greater than 50 dB/octave, they reported that the responses to a 30 dB SL 500 Hz tone with 4 ms rise-time contained "a prominent negative deflection with latencies of 10-15 ms" (29). The latencies of this wave and of the V' wave of our experiment are slightly longer than the SN_{10} component of Davis and Hirsh recorded using a 40 Hz-24 dB/octave filter (8). This difference is probably related to the shorter rise-time (2-2.5 ms) used in their study. It is therefore reasonable to conclude that the V' and SN_{10} components are equivalent. The results of our experiment indicate that the morphology and latency of this component are extremely susceptible to the settings of the high-pass filter used in the recording.

Experiment 2 - Stimulus Presentation Rate

This experiment investigated the interactions between stimulus presentation rate and high-pass filter settings on the brainstem response to 110 dB peak SPL 500 Hz tones. Filter settings of 10, 40 and 70 Hz with rolloff slopes of 6 and 24 dB were used. Averaging was performed over 1000 trials using an averaging sweep of 51.2 ms. The stimuli were presented at rates of 10, 20 and 35/s.

The results of this experiment showed some complex interactions between stimulus presentation rate and the high-pass filter settings. An increased presentation rate resulted in an increased wave V latency at all filter settings, with the major change occurring between the 10 and 20/s rates. The average wave V latencies recorded using the 10 Hz-6dB/octave filter were 8.50, 9.50 and 9.56 ms at stimulus presentation rates of 10, 20 and

35/s. The latency of the V' component did not change significantly with increasing stimulus presentation rate. At the higher filter settings wave V became smaller in amplitude and wave V' became the more prominent response component. The V'/V ratio was largest at the 35/s presentation rate using the 40 Hz-24 dB/octave filter settings. At these settings there was no significant effect of stimulus presentation rate on the V' amplitude.

There were no consistent changes in the V-V' amplitude with changing stimulus presentation rate. The largest amplitude was recorded at a rate of 35/s using the 10 Hz-6 dB/octave filter setting. The middle latency components of the response were variably affected by increasing stimulus presentation rate. At higher rates the later (30+ ms) components were attenuated; the earlier components varied from subject to subject probably because of postauricular muscle reflexes. In certain subjects the V-V' complex at the 35/s presentation rate was superimposed on the residual middle latency components to the previous tone. This is illustrated in Figure 4. This effect probably contributes to the finding that the V-V' amplitude was largest at 35/s.

......................Insert Figure 4 about here.................

The results of this experiment are in general agreement with those of Kodera et al. who recorded responses to 1000 Hz 50 dB SL tones with 5 ms rise time (15). They found that the latency of wave V increased slightly when the interstimulus interval was decreased from 104 to 32 ms. They further reported that the V-V' amplitude (BSR-Na in their nomenclature) showed no change with decreasing interstimulus interval except for a slight increase at the 32 ms interval. The relative stability of the latency and amplitude of V' with changing stimulus presentation rates in our experiment is in agreement with the SN_{10} results of Davis and Hirsh (7).

Experiment 3 - Location of the Reference Electrode

Most authors agree that the optimum recording electrode location for the brainstem response is at the vertex. There is some difference of opinion, however, about the location of the reference electrode. If only wave V is to be evaluated a reference electrode low on the neck (23, 30) gives a greater amplitude recording than a reference electrode on the mastoid or ear lobe (29). If the recording montage is to be used to evaluate wave I as well as wave V, the use of a reference electrode near the cochlea - on the mastoid, earlobe or external auditory meatus - is essential. Electrodes on the mastoid process may also pick up post-auricular muscle reflexes that might distort the later components of the brainstem response. This muscle reflex potential has a very localized scalp distribution, and is much attenuated at small distances from the mid-mastoid region (22, 35). This experiment was therefore designed to assess the effect of the postauricular muscle reflexes on the V and V' components of the brainstem response using reference electrodes located at the mid-mastoid region (at the level of the external auditory meatus) and at the low-mastoid region (2-3 cm lower). Responses were recorded to 500 Hz tones presented at rates of 10, 20 and 35/s with intensities of 110, 90 and 70 dB peak SPL. The electroencephalographic activity from vertex to mid-mastoid and from vertex to low-mastoid electrodes was filtered using a high-pass setting of 10 Hz - 6 dB/octave. Averaging was performed over 2000 trials with a 40.96 ms sweep. Artifact rejection was not employed.

Only 2 out of 8 subjects showed a consistent post-auricular muscle reflex. The waveforms from one subject are plotted in Figure 5. The post auricular muscle reflex consisted of a large mastoid-negative wave peaking at 15-20 ms followed by a mastoid-positive wav at 25-30 ms. The amplitude of this response decreased and its latency increased with decreasing intensity and no definite response was recorded at 70 dB peak SPL. The response was only recordable from the mid-mastoid region. Wave V of the brainstem response was not affected by the reflex. However, at high intensities the initial component of the reflex potential overlapped and attenuated the V' wave of the brainstem response.

....................Insert Figure 5 about here...................

Experiment 4 - Intensity Effects

This experiment evaluated the effects of different stimulus intensities (110, 90 and 70 dB peak SPL) on the brainstem response to 500 Hz tones presented at 10, 20 or 35/s using different high-pass filter settings. Responses recorded between vertex and low-mastoid electrode were averaged over 4000 trials with a sweep duration of 20.48 ms. High-pass filter settings of 10, 20, 40 and 70 Hz with rolloff slopes of 6 and 24 dB/octave were used. The results of this experiment are illustrated in Figures 6 and 7.

...............Insert Figures 6 and 7 about here.................

Decreasing the stimulus intensity resulted in an increase in latency for both the V and the V' components of the response and a decrease in amplitude. These effects were common at all filter settings and at all stimulus presentation rates. At the 10 Hz-6 dB/octave filter setting and at a tone presentation rate of 10/s the average latencies of wave V at intensities 110, 90 and 70 dB peak SPL were 8.72, 9.68 and 12.37 ms. At 35/s the latencies were 9.41, 11.48 and 13.22 ms. The average latencies of V' were 14.75, 15.64 and 16.63 at 10/s and 15.21, 15.96 and 17.05 at 35/s. The V-V' amplitudes were 0.63, 0.45 and 0.32 µV at 10/s and 0.87, 0.50 and 0.29 µV at 35/s.

The effects of changing the filter settings were similar at 90 and 70 dB to those described in Experiment 1 using the 110 dB tones. The latencies of both wave V and wave V' decreased with both increasing filter cutoff setting and increasing rolloff slope. For the V' component the latency changes were greater than for the V wave and the effect of increasing rolloff slope was much greater at the higher filter cutoff settings. The V-V' amplitude decreased with increasing filter settings and with increasing rolloff slopes. Again there was an interaction between the two effects such that the effect of rolloff slope was not significant at 10 Hz and increased from 20 to 70 Hz. The differences in amplitude related to filter settings were much less at 70 dB as compared to 110 dB but the differences were still significant at 70 dB. The amplitude effects are shown in Figure 7 where, for clarity, only the results at 35/s are plotted. The morphology of the V-V' complex changed in much the same manner at 90 and 70 dB as at 110 dB in Experiment 1. The V' component was most prominent at filter settings of 40 and 70 Hz.

The effects of changing the rate of stimulus presentation were similar to those obtained in experiment 2. Increasing the rate of tone presentation caused an increased wave V latency. There was no effect on V' latency except that the combination of low intensity, high filter setting and high rolloff slope caused a decrease in V' latency with increasing stimulus presentation rate. There was no effect of increasing rate on the V-V' amplitude except at high filter settings and low intensity where the amplitude were smaller at 35/s rates.

The results of this experiment show quite clearly that at all intensities larger brainstem responses are recorded using the lower high-pass filter settings and rolloff slopes. The optimal settings appear to be 10 Hz at either 6 or 24 dB/octave rolloff and 20 Hz at 6 dB/octave rolloff. The recognizability of an average waveform, however, depends upon both the amplitude of the response and the amount of background electroencephalographic noise remaining after averaging. It is possible, therefore, that higher filter settings and/or higher rolloff slopes may be of assitance in certain clinical conditions where the background noise level in the 10-40 Hz range is high - for example in patients who are sedated or who have high levels of muscle activity. The use of these higher settings on the high-pass filter will alter the brainstem response morphology to give a prominent vertex-negative V' component. There were no consistent effects of stimulus presentation rate on the amplitude of the response. Because of the decreased time necessary for averaging, it is therefore preferable to use the faster stimulus presentation rates.

Experiment 5 - Stimulus Rise-times

This experiment evaluated the effect of different rise-times on the brainstem response to tones of different frequencies. Tones with rise-times of 1, 2, 5 and 8 ms and equivalent fall-times were presented at frequencies of 500, 1000, 2000 and 4000 Hz and at an intensity of 100 dB peak SPL at a rate of 35/s. Averaging was carried out over 2000 trials using a sweep duration of 25.6 ms.

The average wave V latencies and amplitudes for eight subjects are plotted in Figure 8. There were significant increases in V latency with decreasing stimulus freuency and with increasing rise-time. There was also an interaction between these two effects such that the increase in latency with increasing rise-time was greater at the lower frequencies.

Regression lines were calculated for the rise-time effects at each frequency. The equation for these regression lines was: latency of wave V= a (rise-time) + b. The slopes (a) of these lines were 0.44, 0.40, 0.30 and 0.26 at 500, 1000, 2000 and 4000 Hz. The respective latency intercepts (b) were 6.88, 6.48, 6.33 and 6.11 ms.

................Insert Figure 8 about here.....................

These results show a definitely increasing effect of rise-time on V latency at the lower frequencies. One possible explanation for this could be the increased spread of the acoustic energy in the spectra of low-frequency tones with short rise-times. These rapid-onset tones could thus evoke responses through more basal regions of the cochlea than the tones with longer rise-times. The regression line calculated for 500 Hz 100 dB tones presented in notched noise (data from Experiment 6), however, showed a slope of 0.49 as well as a generally increased latency with a latency intercept of 8.65 ms. The regression line for the 2000 Hz 100 dB tones in notched noise had a slope of 0.23 and an intercept of 7.12 ms. It therefore seems that the alteration in slope with stimulus frequency is a true function of stimulus frequency and not an artifact of acoustic distortion.

Several researchers have reported an increase in wave V latency with increasing stimulus rise-time (3, 6, 13, 17). Brinkmann and Scherg (3) introduced the concept of "virtual trigger time" which appears to represent the point on the rise-time of the stimulus when the majority of nerve fibers connecting to the brainstem response generator are activated.

This virtual trigger time is a function of both the rise-time and the intensity of the stimulus. Our results indicate that it is also a function of stimulus frequency. At the lower frequenies, where there is locking of nerve fiber activation to stimulus phase, increasing the rise-time could delay the time of major nerve fiber activation by one or more stimulus cycles. This delay would be greater the lower the frequency of the stimulus.

The V-V' amplitude of the brainstem response showed significant changes with both stimulus frequency and rise-times. These effects are shown on the right of Figure 8. The amplitude was greater at the lower frequencies and decreased with increasing rise-time. The major change in amplitude occurred between the rise-times of 5 and 8 ms.

The effect of stimulus rise-time on the brainstem response amplitude appears to differ between white noise and tonal stimuli. Varying the rise-time of white noise bursts up to 10 ms does not cause any definite change in the brainstem response amplitude (3, 13). Our results and those of Kodera et al (17) indicate a definite decrease in amplitude at longer rise-times with tones. This is particularly true at rise-times of greater than 2.5 ms. At shorter rise-times there may not be any change in amplitude (6). It is possible that the locking of nerve impulses to the phase of low-frequency stimuli may cause more jitter at longer rise-times in tonal as opposed to noise stimuli. This jitter would result in broader responses of lower amplitude. Our results indicate that for tonal stimuli rise-times of 5 ms or shorter would be preferable since at longer rise-times the brainstem response is quite attenuated.

Experiment 6 - The Effects of Notched Noise

This experiment was designed to investigate the frequency-specificity of the brainstem responses to tones with different rise-times. Tones of 500 and 2000 Hz were presented at intensities of 120, 100, 80 and 70 dB peak SPL either alone or mixed with notched noise (with the rejected band centered on the frequency of the tone). The noise intensity measured in RMS SPL was 25 dB less than the tone intensity measured in peak SPL. Stimuli were presented at 35/s and averaging was carried out over 2000 trials with a sweep duration of 25.6 ms. The responses at 80 and 70 dB were replicated. The rationale for this experiment was that if the notched noise caused the response to change, the response to the tone alone was in part mediated by frequencies in the tone away from its nominal frequency.

The effect of the notched noise on the wave V latency was quite complex. The average data from eight subjects are plotted in Figure 9. The latency of wave V in the 500 Hz response was significantly increased by notched noise at all intensities for the 1 ms rise-times, at 100 dB or more for 2 ms, at 80 dB or more for 5 ms, and at 100 dB or more for 8 ms. The latency of the 2000 Hz response was significantly increased by the notched noise at 80 dB or more for the 1 ms rise-time, and at 100 dB or more for 2 ms. There were no significant effects of the notched noise on the 2000 Hz response latency for rise-times of 5 or 8 ms.

.....................Insert Figure 9 about here................

The notched noise significantly reduced the amplitude of the brainstem response. This reduction in amplitude was greater at the higher intensities and at the lower rise-times. At 500 Hz there were significant amplitude differences with the notched noise at 80 dB or more for the 1 and 2 ms rise-times, at 100 dB or more for the 5 and 8 ms rise-times. At 120 dB the average V-V' amplitude for 5 ms rise-time tones was 1.20 µV when the tones were alone and 0.87 µV when in notched noise. At 70 dB the amplitudes were 0.42 and 0.32 µV. At 2000 Hz there were significant differences in the V-V' amplitude at 100 dB or more for all rise-times. At 120 dB the average amplitude for 5 ms rise-times was 1.16 µV when the tones were presented alone and 0.56 µV when in notched noise. At 70 dB the amplitudes were 0.37 and 0.36 µV.

Two possible explanations for the effects of notched noise can be considered. The first is that the masking noise decreases the effective intensity of the tone, thereby decreasing the amplitude and increasing the latency of the response. The second is that the notched noise limits the response to a particular area of the cochlea, masking out those parts of the response that are mediated through other regions of the cochlea activated by the spread of acoustic energy in the brief tone or by the dynamics of the travelling wave. The first explanation is probably not a major cause of the experimental findings. It does not explain the different effects of the masking noise at the different frequencies or at the different intensities. Furthermore, increasing the intensity of the masking noise has little effect on the amplitude or latency of the 500 Hz response (23). The second line of explanation can account reasonably well for all of the observations. The latency changes are most evident at 500 Hz because the 500 Hz response latency is mainly determined by the higher frequency regions of the cochlea activated by the spread of frequencies in the brief tone. These high-frequency regions are more readily synchronized and give a sharp-peaked component in the response that determines the latency. The notched noise masks the response from the higher frequency region leaving a braod, longer latency response from the 500 Hz region of the cochlea. At 2000 Hz the notched noise has less effect because of the higher frequency-specificity of the 2000 Hz stimulus (cf Figure 1) and because the response cannot shift far to an earlier or more synchronizable region of the cochlea. The amplitude changes occur at both frequencies because of the masking of the response to frequencies outside of the rejection band of the notched noise. The decreasing effects of notched noise at lower intensities occur because at the lower intensities the skirts of the tone frequency spectrum become subthreshold.

If we therefore accept the second line of explanation as correct, then the results of this sixth experiment indicate that the brainstem response to brief tones at intensities of 100 dB or more is not frequency-specific regardless of the rise-time of the tone. At rise-times of 1 or 2 ms the response to 500 Hz tones is not even frequency-specific at lower intensities.

CONCLUSIONS

The largest brainstem responses to low frequency tones are recorded using low high-pass filter settings (10 or 20 Hz) and low rolloff slopes. Under these conditions a large clear vertex-positive wave is recorded. At higher high-pass filter settings, particularly if higher rolloff slopes (24-48 dB/octave) are used, the response is smaller and tends to show a prominent vertex-negative wave.

There are no significant changes in the amplitude of the response recorded using low high-pass filter settings and low rolloff slopes when stimulus presentation rate of up to 35/s are used. There is, however, a significant increase in the latency of wave V at the higher presentation rates.

Postauricular muscle reflexes are evoked by high intensity tones and can distort the brainstem response recorded using a mid-mastoid reference electrode. A reference located lower down on the mastoid is therefore preferable. If the wave I recording is not essential, the reference electrode can be located on the lower part of the neck.

Tones with longer rise-times have greater acoustic specificity. They elicit responses with longer latency and smaller amplitudes. In general, latency increases of 0.2-0.5 ms occur with increases of 1 ms in rise-time. The exact relationship between rise-time and latency is a complex function of both the frequency and the intensity of the tone. The amplitude of the response falls off dramatically with rise-times of greater than 5 ms. A 5 ms rise-time is perhaps the best compromise between frequency-specificity and response recognizability.

The effects of notched noise indicate that even at this 5 ms rise-time the brainstem response is not frequency-specific at intensities of 100 dB peak SPL or more. It therefore appears advisable to use notched noise masking for brief tones of high intensity.

The results of these experiments can be summarized as a set of recommendations: high-pass filter settings of 20 Hz with 6 dB/octave rolloff, stimulus presentation rates of 35/s, a low-mastoid reference electrode, tones of 5 ms rise-time, notched noise masking. These recommendations must be tempered by the fact that under certain conditions other stimulation and recording parameters may be more effective. Nevertheless, for the most part these recommendations should allow efficient brainstem evoked potential audiometry using tones.

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FIGURE LEGENDS

Figure 1 - The effect of different rise and fall times on the acoustic spectra of 500 and 2000 Hz tones. Tones were generated by the TN-3000 system with rise-times of 1, 2, 5 and 8 ms, equivalent fall times, and plateau durations of 0.01 ms. The tones were presented through a TDH-49 earphone at an intensity of 115 dB peak SPL. The acoustic signal was recorded using a Brüel and Kjaer microphone and analyzed using a laboratory-programmed TN-1500 signal analyzer. The power spectral density function for each tone is plotted between 100 and 10,000 Hz using logarithmic intensity and frequency axes. The intensity axes are arbitrary (0 dB is approximately 40 dB SPL).

Figure 2 - The effects of different high-pass filter settings on the brainstem response to 110 dB peak SPL 500 Hz tones presented at a rate of 10/s. Recordings were taken between vertex and mid-mastoid electrodes and each tracing represents the average of 2000 responses. Relative negativity at the vertex is represented by an upward deflection. The vertex-positive wave V, indicated by the open triangles, is most prominent at the lowest settings of the high-pass filter. The vertex-negative V' component, indicated by the filled triangle, is particularly prominent at the 40 Hz 24 dB/octave filter setting. Subject D.S.

Figure 3 - The effects of changing high-pass filter settings and rolloff slopes on the brainstem response to 500 Hz tones. The

average data from eight subjects are plotted. The latency of wave V is shown on the left and of wave V' on the right. The V-V' amplitude is plotted in the center.

Figure 4 - The effects of stimulus presentation rate and high-pass filter settings on the brinstem response to 500 Hz tones. The duration of the averaging sweep was 50 ms. At 35/s the interstimulus time (28.6 ms) is less than the sweep duration and therefore a second response is initiated prior to the end of the sweep. This is illustrated in the figure by the dotted lines. As well, this second response has been superimposed on the first in the initial portion of the tracing. In this subject (S.S.) the increase in stimulus presentation rate from 20/s to 35/s causes a decrease in the amplitude of wave V (open triangle) and an increase in the amplitude of V' (filled triangle). This is probably because of the superimposition of these components on the negative wave occurring at 40-45 ms after the preceding tone. When the high-pass filter setting is changed, the V' component has a shorter latency and small amplitude.

Figure 5 - Postauricular muscle reflexes. Responses were recorded to 110, 90 and 70 dB peak SPL 500 Hz tones presented at a rate of 10/s. The dotted tracings represent recordings from vertex to low-mastoid electrodes, and the continuous tracings represent recordings from vertex to mid-mastoid electrodes. High-pass filtering was performed at 10 Hz with a 6 dB/octave rolloff slope. Each tracing represents the average of 2000

responses and negativity at the vertex is represented by an upward deflection. AT 110 dB this subject (P.F.) exhibited a large muscle reflex that decreased in amplitude at 90 dB and disappeared at 70 dB. The muscle reflex was very focal in its scalp distribution and did not show up in the recordings made using the low-mastoid electrode. The V component of the brainstem response (filled triangles) was not affected by the location of the reference electrode. However, the muscle reflex began before the peak of the V' wave and distorted any measurement of this component.

Figure 6 - The effects of high-pass filter settings and stimulus presentation rate on the response to 500 Hz tones. The waveforms in this figure each represent the average of 4000 individual responses from subject S.S., obtained using a vertex to low-mastoid derivation and a high-pass filter rolloff slope of 24 dB/octave. With decreasing intensity wave V (open triangles) showed increasing latency and decreasing amplitude. The vertex-negative V' component (filled triangles) is best seen at the 40 and 70 Hz filter settings. WIth decreasing intensity this V' wave also increased in latency and decreased in amplitude.

Figure 7 - The effects of high-pass filtering on the amplitude of the brainstem response to 500 Hz tones of different intensities. The average V-V' amplitude data from 8 subjects is plotted at tone intensities of 110, 90 and 70 dB peak SPL. To simplify the figure only the 35/s data from Experiment 4 are plotted.

Increasing the filter setting or the rolloff slope causes a decreased amplitude of the brainstem response. This effect is smaller but still significant at the lower intensities. At each intensity the largest wave V amplitudes are recorded using the 10 Hz filter settings with either the 6 or 24 dB/octave rolloff or using the 20 Hz setting with the 6 dB rolloff.

Figure 8 - The latency and amplitude of the brainstem response to tones of different frequencies and rise-times. The tones had rise-times of 1, 2, 5 and 8 ms, plateau durations of 0.01 ms, and fall-times equal to the rise-times. They were presented at an intensity of 100 dB peak SPL and at a rate of 35/s. The average data from eight subjects are plotted in this figure. The wave V latency is plotted on the left and the V-V' amplitude on the right.

Figure 9 - The effect of notched noise on the latency of the brainstem response to tones. Tones of 500 Hz and 2000 Hz were presented at 35/s either alone (continuous lines) or in notched noise (dotted lines) at 25 dB below the tone intensity. The average latencies of wave V for eight subjects are plotted for tone rise-times of 1, 2, 5 and 8 ms. At 500 Hz the notched noise causes a prolongation in the latency of the response. This is significant at all intensities for the 1 ms rise-time but only at the 100 and 120 dB intensities for the 8 ms rise-time. At 2000 Hz the notched noise does not affect the latency at the 5 or 8 ms rise-times. At the shorter rise-times there is a prolongation of

the latency at the higher intensities.

Figure 1

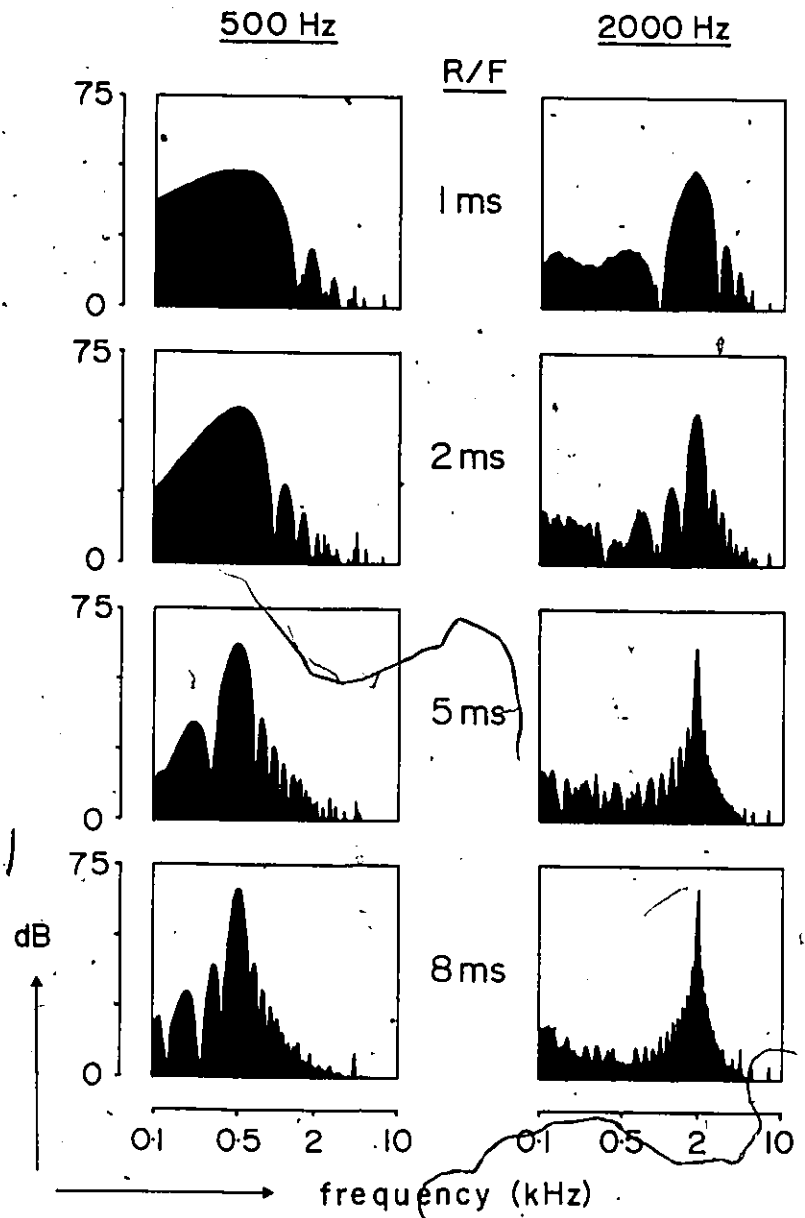


Figure 2

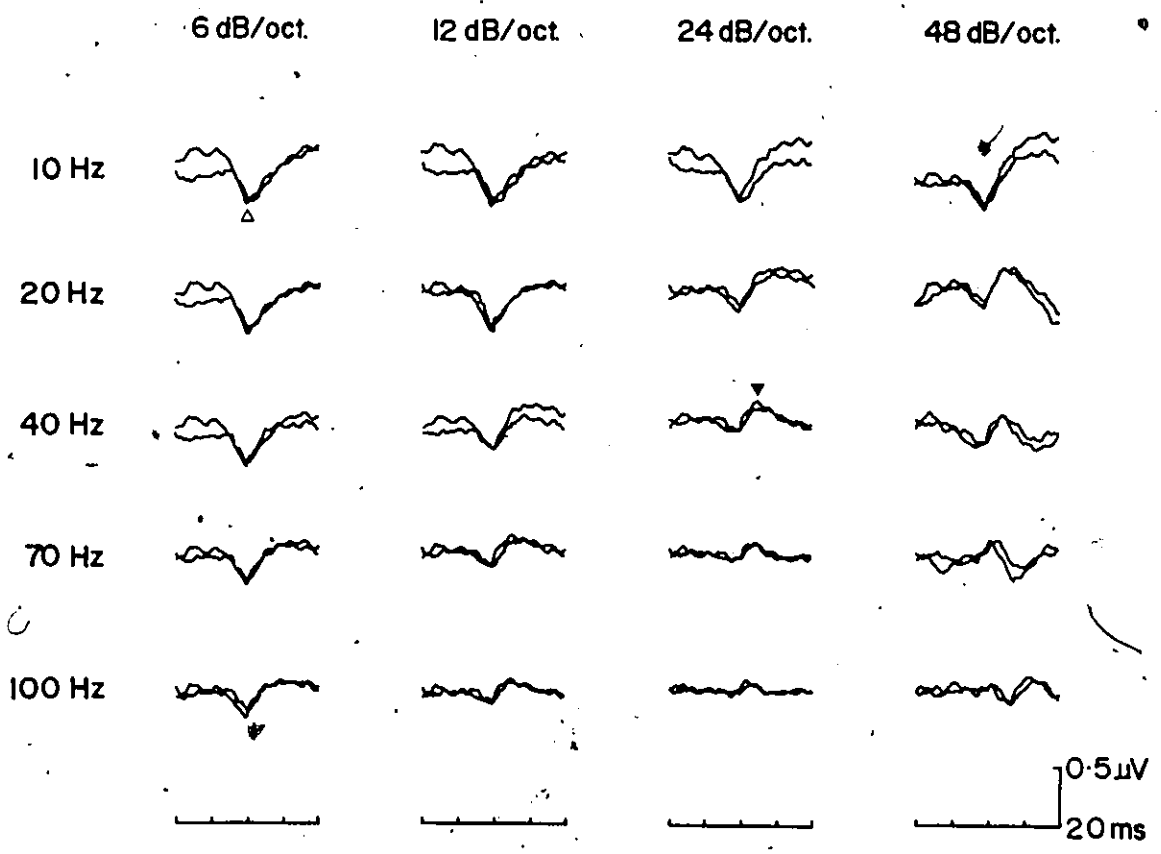

6 dB/oct.
12 dB/oct.
24 dB/oct.
48 dB/oct.
10 Hz
20 Hz
40 Hz
70 Hz
100 Hz
0·5 μV
20 ms

Figure 3

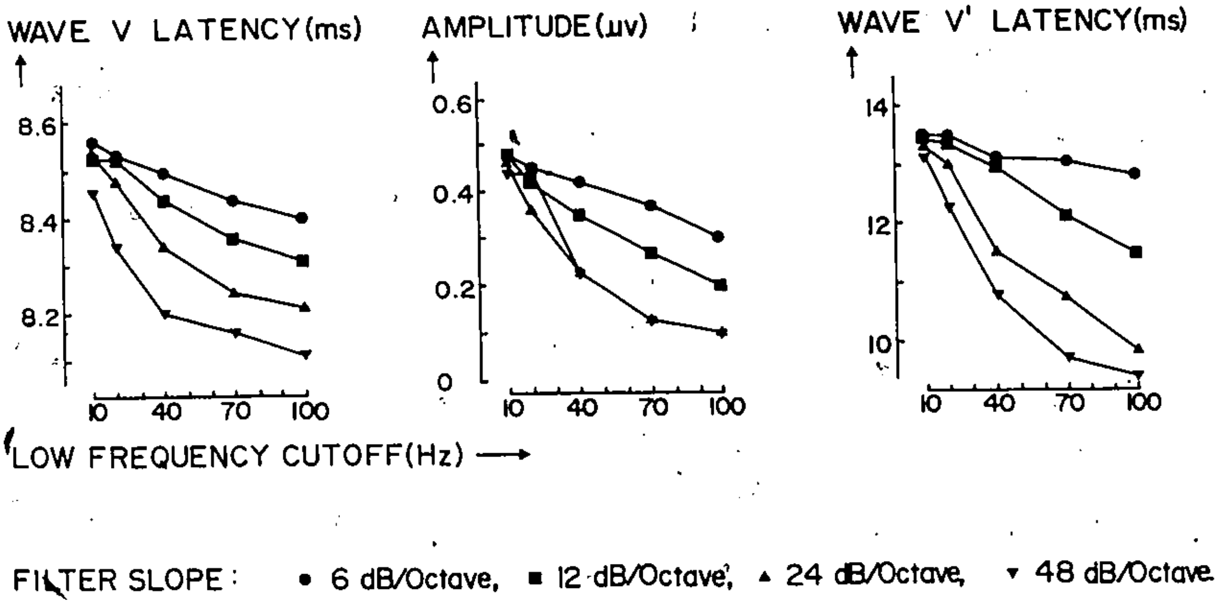

WAVE V LATENCY(ms)
8.6
8.4
8.2
AMPLITUDE(µv)
0.6
0.4
0.2
0
WAVE V' LATENCY(ms)
14
12
10
10
40
70
100
LOW FREQUENCY CUTOFF(Hz) →
FILTER SLOPE: ● 6 dB/Octave, ■ 12 dB/Octave, ▲ 24 dB/Octave, ▼ 48 dB/Octave

Figure 4

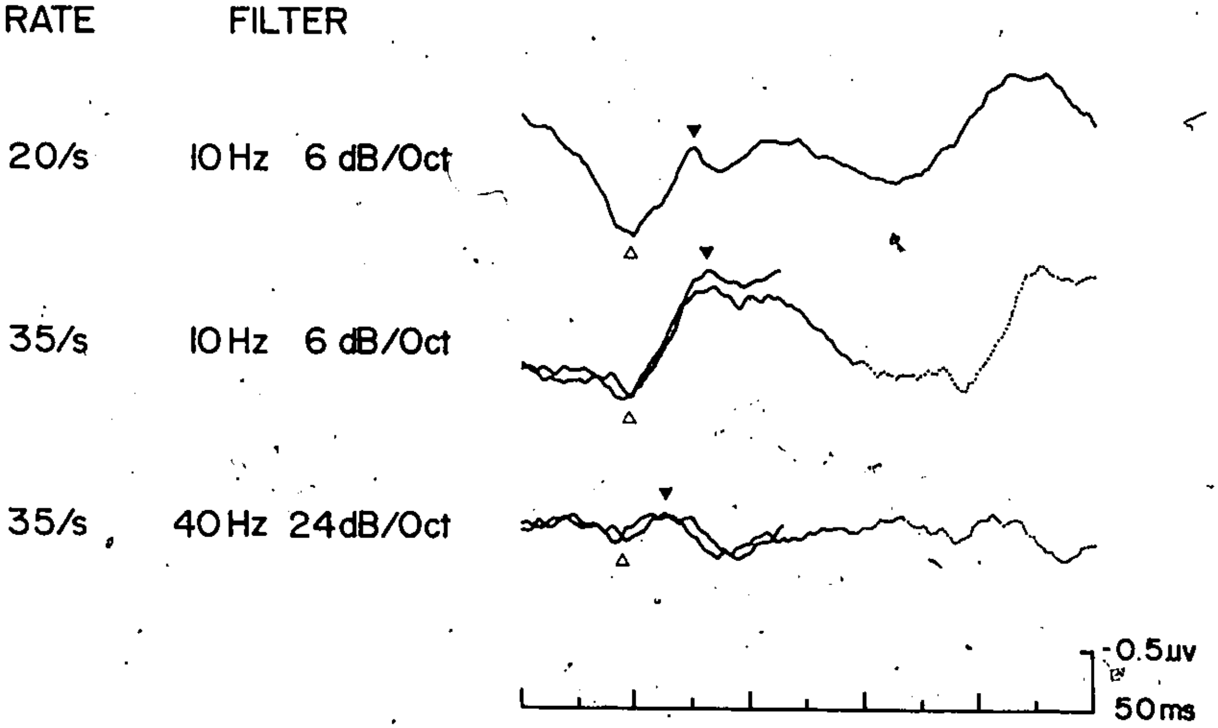

RATE
FILTER
20/s
10 Hz 6 dB/Oct
35/s
10 Hz 6 dB/Oct
35/s
40 Hz 24 dB/Oct
0.5 µv
50 ms

Figure 5

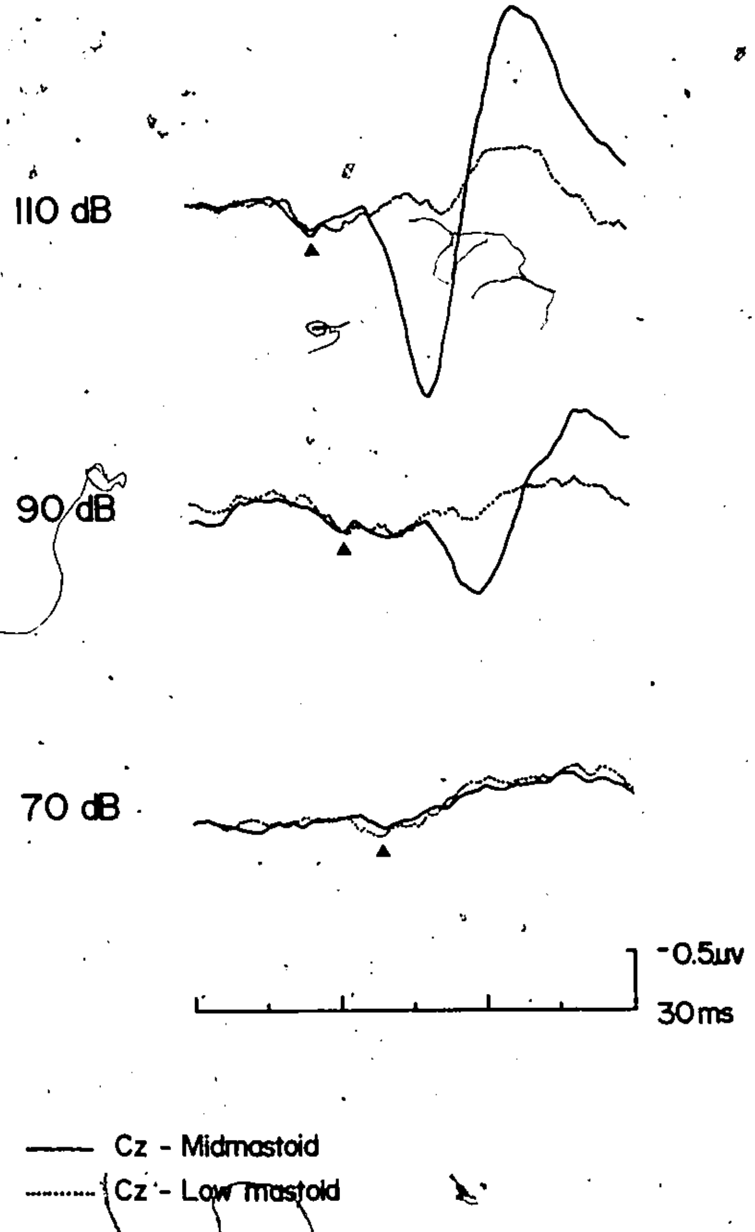


Figure 6

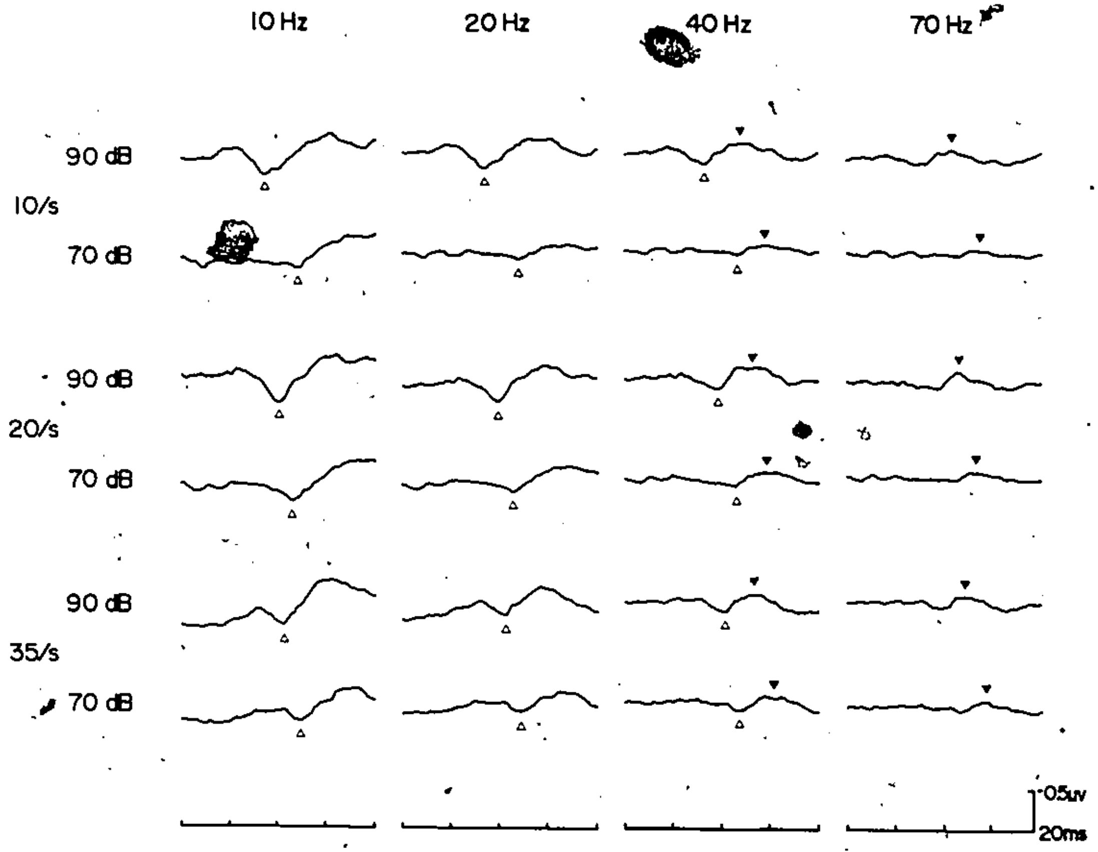
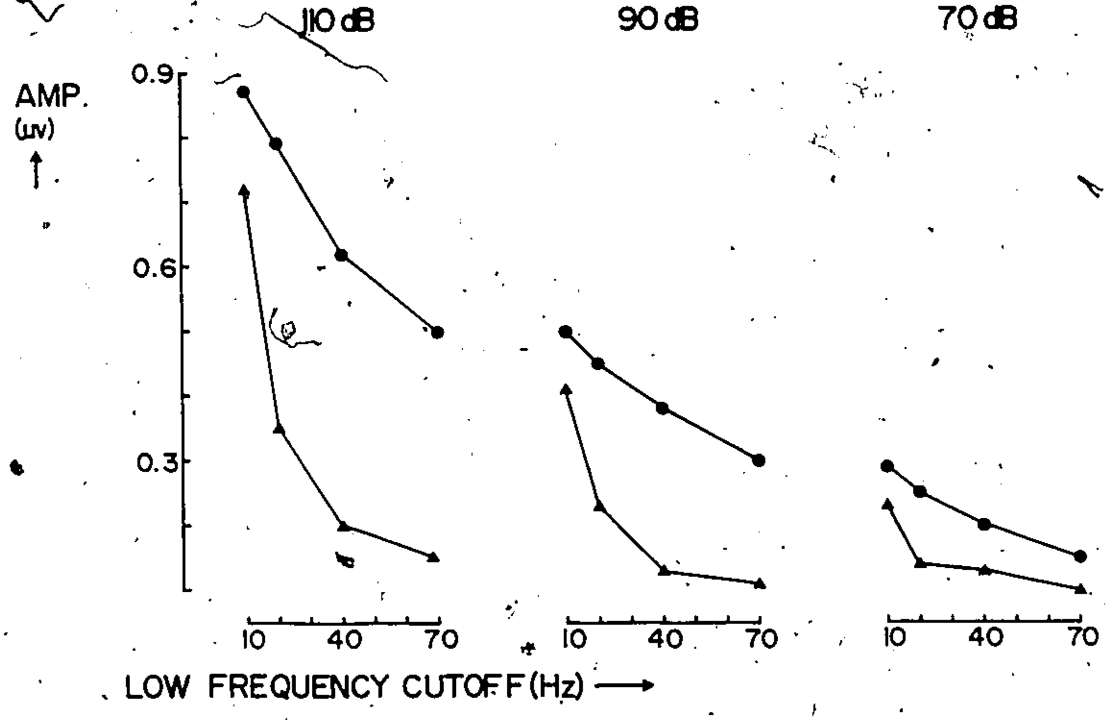

10 Hz
20 Hz
40 Hz
70 Hz
90 dB
10/s
70 dB
90 dB
20/s
70 dB
90 dB
35/s
70 dB
·05uv
20ms

Figure 7



FILTER SLOPE: ● 6 dB/Octave, ▲ 24 dB/Octave.

Figure 8

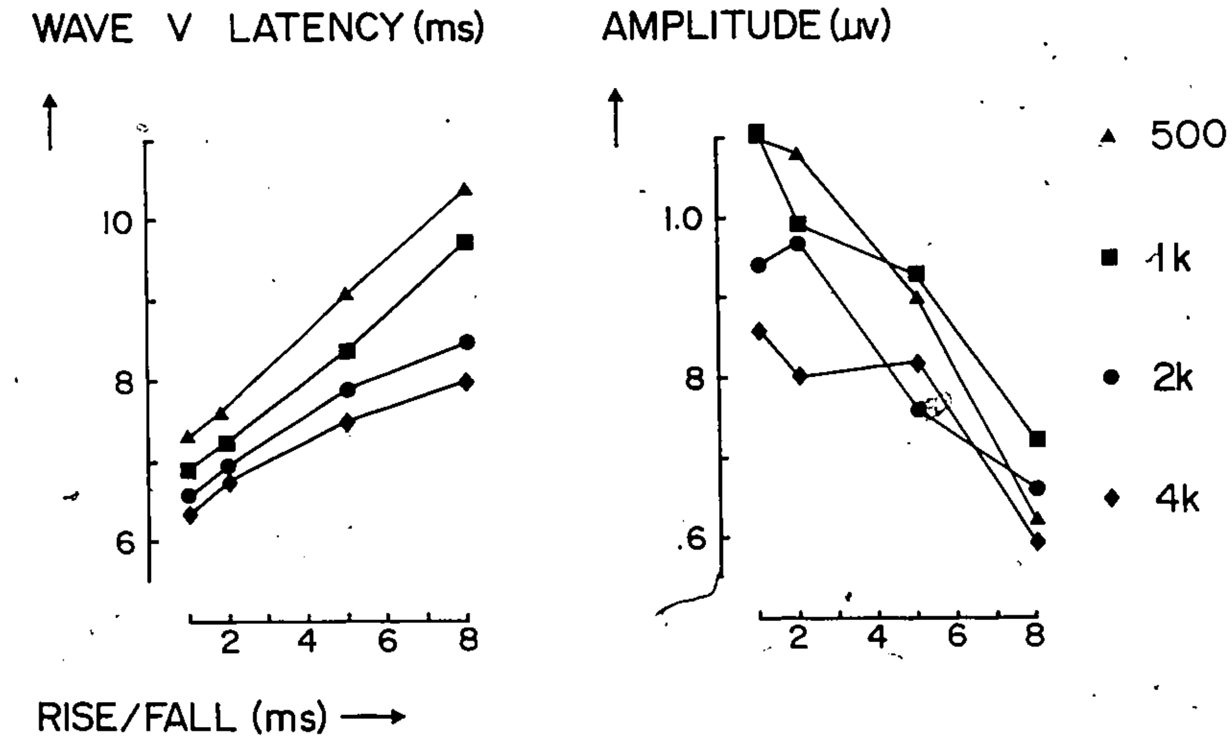
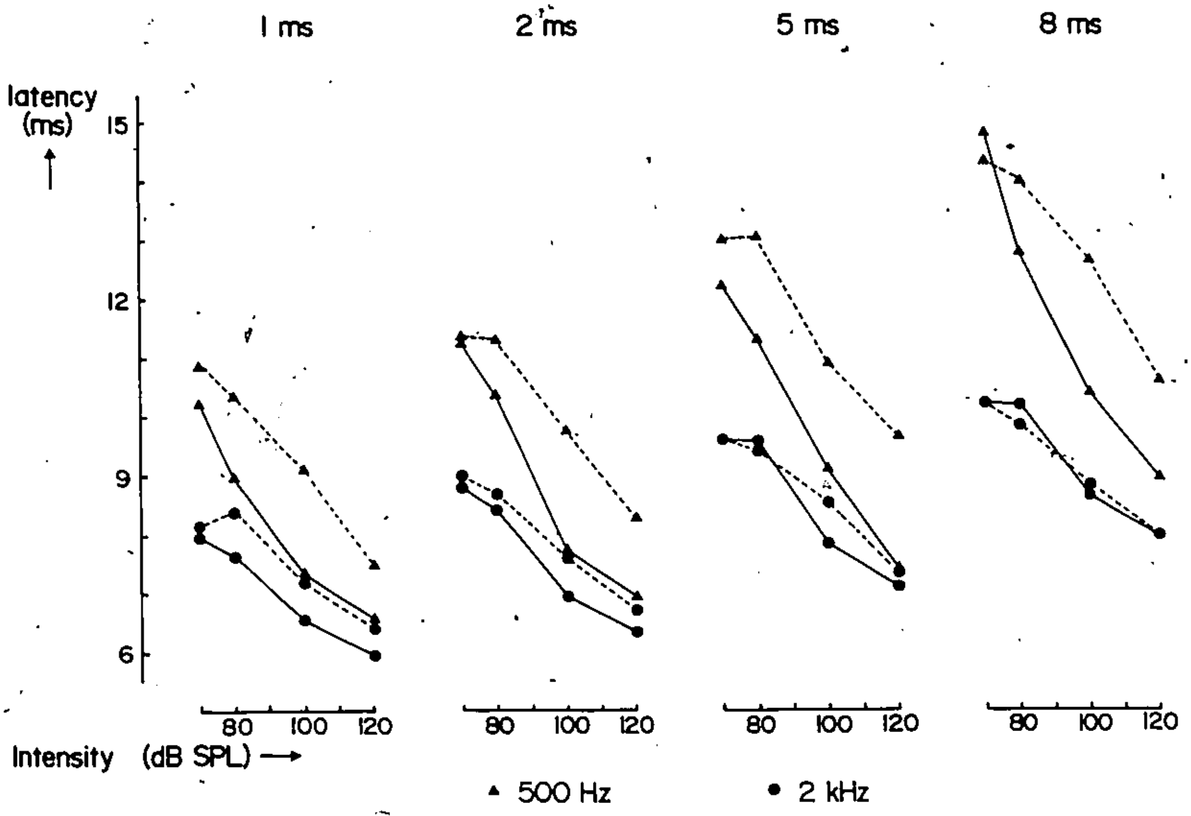

WAVE V LATENCY (ms)
10
8
6
2
4
6
8
RISE/FALL (ms) ⟶
AMPLITUDE (µv)
1.0
.8
.6
2
4
6
8
▲ 500
■ 1k
● 2k
◆ 4k

Figure 9


1 ms
2 ms
5 ms
8 ms
latency (ms) ↑
15
12
9
6
80
100
120
Intensity (dB SPL) ⟶
▲ 500 Hz
● 2 kHz

Ear and Hearing

HUMAN AUDITORY STEADY STATE POTENTIALS

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ABSTRACT

The auditory steady state potentials may be an important technique in objective audiometry. The effects of stimulus rate, intensity, and tonal frequency on these potentials were investigated using both signal averaging and on-line Fourier analysis. Stimulus presentation rates of 40 - 45/s result in a 40-Hz sinusoidal response which is about twice the amplitude of the 10 and 60/s responses. No significant effects of subject age or sex were seen. The 40/s response shows a linear decrease in amplitude and a linear increase in latency when stimulus intensity is decreased from 90 to 20 dB nHL. This response is recordable to within a few dB of behavioral threshold. Stimuli of different tonal frequency give similar amplitude/rate functions, with absolute amplitude decreasing with increasing tonal frequency. Signal averaging and Fourier analysis provide nearly identical amplitude/rate, amplitude/intensity, and latency/intensity functions. Both methods of analysis may be used, therefore, to record the 40-Hz steady state potential. Fourier analysis, however, may be the faster and less-expensive method. Furthermore, techniques ("zoom") are available with Fourier analysis to study the effects of varying stimulus parameters on-line with the Fourier analysis procedure.

KEY WORDS: Auditory evoked potential; Fourier analysis; Middle latency response; Steady state potential.

The auditory evoked potentials have recently become very important in objective audiometry. Many different auditory responses can be recorded from the human scalp and each may provide important information about auditory function (17). The auditory evoked potentials may be classified as transient responses, sustained responses and steady state responses (16). A transient response is elicited by a rapid change in the auditory stimulus whereas a sustained response is elicited by the continuation of a stimulus. Transient and sustained responses are recorded using stimulus rates that allow the response to one stimulus to be finished before the next stimulus is presented. Steady state potentials, however, are elicited by stimuli presented at a sufficiently high rate to cause an overlapping of the responses to successive stimuli. This results in a periodic response with a constant phase relationship to the repeating stimulus. Transient and sustained responses are best recorded using signal averaging. Steady state responses can be recorded either by signal averaging or by frequency-based analysis procedures. Transient responses are usually described in terms of the amplitudes and latencies of their components; steady state potentials are described by their amplitude and phase.

Until recently the human steady state potentials were mainly studied in the visual modality (18,19,20,21,22,23,24), with only occasional reports of auditory steady state responses (4). The description of an auditory 40-Hz event related potential (ERP) in 1981 by Galambos, Makeig and Talmachoff (9), however, re-awakened interest in the auditory steady state potentials and their possible use in objective audiometry. In their initial report, Galambos et al. showed that when stimuli are presented at 40/s, the middle latency responses have an amplitude some 2 or 3 times greater than when the stimuli are presented at the conventional 10/s rate. They demonstrated that the amplitude/rate function of the response had a large peak at 40/s, a smaller peak at its subharmonic 20/s, and minima at 25 and 55/s. They attributed the greater amplitude at 40/s to the superimposition of the successive negative-positive peaks. Each negative-positive cycle in the 10/s response lasts approximately 25 ms, and at 40/s these cycles would occur in phase and sum, producing a larger response. The successive cycles would be out-of-phase at a rate of approximately 27/s (1/37.5 ms). The 40-Hz auditory potential can be recorded to tones of low (250 & 500 Hz) as well as high (5000 Hz) frequency (9). As tonal frequency increases the amplitude and latency of the 40-Hz response decreases. As stimulus intensity is decreased, the amplitude decreases and the latency increases (9). Most importantly, Galambos and his colleagues reported that the 40-Hz response could be recorded at levels very close to behavioral thresholds. These results, which have been replicated in other laboratories (3,10,11,12,27), suggest that the 40-Hz response may become an important tool in the objective evaluation of auditory thresholds.

Since the auditory system is nonlinear, the transient and steady state potentials may provide complementary views of the system's functions (18,20,22,23). In a completely linear system, the steady state responses are equivalent to the simple superimposition of the transient responses. Transient and steady state responses then give essentially the same information. If the system is nonlinear, however, steady state potentials may not be equivalent to the simple superimposition of transient responses but will show evidence of nonlinearities such as the relative refractory period. It would then be useful to record both the transient and steady state responses.

The present paper reports the results of four experiments on the human auditory steady state potentials. Our purposes were to replicate and extend the results of Galambos and his colleagues, and to see if frequency-analysis techniques could provide the same results as time-based signal averaging. The frequency-analysis instrument for our experiments was a Fourier analyzer (22). This simple and relatively inexpensive instrument calculates the amplitude and phase of that part of the recorded activity that has the same fundamental frequency as the rate of stimulus presentation.

GENERAL METHODS

Subjects

Nine males and eleven females, between the ages of 21 and 61 (mean age = 27.4 years), participated in one or more of the experiments. None had any history of audiological or neurological problems. During the experiment the subjects sat or reclined in a quiet room. The subjects were instructed to stay awake and their state was continually monitored to ensure that they did not fall asleep. Most subjects read a magazine or book during the recordings.

Stimulus Generation

Tonebursts with linear rise and fall times of 4 ms each and a plateau duration of 2 ms were produced by electronically gating a 500, 1000, 2000 or 4000 Hz sinewave signal. This signal was produced by a Tektronix (model FG501) function generator, and gated by a Grason Stadler (model 1287B) electronic switch that was timed by a Grason Stadler (model 1216) timer. The onset-phase of the tone was random. The inter-stimulus interval (ISI) was controlled by a Wavetek (model 159) waveform generator. The toneburst was amplified (Grason Stadler, model 1288), attenuated (Grason Stadler, model 1293), and presented to the subject through an unshielded TDH-49 earphone mounted in a MX41/AR cushion. The stimuli were calibrated using a Brüel and Kjaer 2209 sound level meter and NBS 9-A earphone coupler [Brüel and Kjaer type 4152(DB 0909) with a 1-inch microphone type 4144]. The normal hearing level (nHL) for the tonebursts used in the studies reported here were obtained in a pilot study in which 10 audiologically-normal subjects were tested in an IAC sound-attenuated chamber using Békésy tracings. The normal hearing level for the 500 Hz toneburst, presented at a rate of 10 per second, is 27.5 dB peak SPL.

EEG Recording Procedures

Electroencephalographic (EEG) signals were obtained using Grass gold-plated cup electrodes attached at the vertex and on the mastoid ipsilateral to stimulation using saline gel and collodion-impregnated gauze. Inter-electrode impedances were below 3 kOhms. The EEG was amplified using a Beckman R-611 polygraph amplifier (bandpass 5 - 1900 Hz; 6 dB/octave slope). These signals were further amplified and averaged using a Tracor Analytic 3000 Clinical Evoked Potential System (bandpass 10 - 1500 Hz; 12 dB/octave slope). This relatively-wide band was chosen to prevent any distortion of the recorded waveform (25,28). Trials containing amplitudes greater than ±50 µV were automatically rejected from averaging. Replicate tracings of 2000 responses each were recorded using either a 51.2 ms or 102.4 ms sweep time. These averaged responses were then stored on floppy-disks. The EEG signals could also be routed to an analogue Fourier analyzer constructed based on the schematics published by Regan (22). After being amplified by the Beckman polygraph, the EEG was further amplified using a Tektronix (model AM502) amplifier (bandpass 1 - 10,000 Hz; 6 dB/octave slope) and fed to the Fourier analyzer, which calculated the mean phase and amplitude of the EEG at the frequency of stimulus-repetition. A

Digital Equipment MINC-11 computer controlled the waveform generator and calculated the average amplitude and phase of the signals being processed by the Fourier analyzer.

Response Analysis

The principle of the Fourier analyzer is diagrammed in Figure 1. An oscillator (O) triggers the stimulus generator (S) at a repetition rate of F Hz. While the subject receives the auditory stimulation his EEG is amplified (A) and fed to the Fourier analyzer to be multiplied (M) by the sine and the cosine of the stimulus-repetition frequency. These multiplications convert that component of the EEG having the same frequency as the stimulus-repetition rate into a steady d.c. output. All frequency components which are outside of the narrow bandpass of this system (0,002 Hz at -6 dB (18)) are converted to a.c. outputs. The outputs of these multipliers are then low-passed filtered (F) to remove the a.c. "noise", and the resultant d.c. outputs (x,y) are used to calculate (C) the amplitude and phase of the fundamental frequency component using the formulae presented at the bottom of Figure 1.

Insert Figure 1 about here

The amplitude of the averaged evoked potential was measured as the average of the peak-to-peak amplitudes in the waveform, with the number and location of these determined using a sinusoidal template of the same frequency as the rate of repetition. The latency to the first major vertex-positive peak in the averaged 40-Hz waveform was recorded. At higher rates of stimulus presentation, however, one cannot actually associate any individual response cycle with a particular stimulus cycle. A "derived latency" of the averaged steady state evoked potentials was therefore obtained using the method proposed by Diamond (5,6). For each subject, linear regressions were performed on the latency/ISI plots for the prominent positive and negative peaks of the response between 35/s and 55/s, and the averag latency intercept taken as the derived latency. The amplitude and phase of the responses evaluated on the Fourier analyzer were calculated by the MINC-11 computer. Replicate responses were combined using vector-averaging. This allowed us to calcluate the average amplitude and phase of the response over a period of time or over several replications. The amplitude measurements from the Fourier analyzer were calibrated on the basis of peak-to-peak voltages. Regan (18) has described the calculation of an "apparent latency" from the phase data obtained at several repetition rates. For each subject the apparent latency (in seconds) was calculated by obtaining the slope of the linear portion of the phase/repetition-rate function (35 - 55/s) and dividing it by 360.

The data were analyzed using linear regressions and repeated measures Analyses of Variance. Results were considered significant at $p<0.01$.

RESULTS AND DISCUSSION

Experiment 1: Stimulus Presentation Rate

The purposes of this experiment were to replicate the rate study originally reported by Galambos et al. (9) in 1981 and to assess the intersubject variability of the response. Averaged responses were recorded from 16 subjects (8 male, 8 female; mean age = 27.9 years) in response to the 500 Hz tonebursts presented at 60 dB nHL at rates of 10 to 60/s, using steps of 5/s. The order of selection of these rates was randomized. Replicate averages of 2000 evoked potentials each were analyzed using either a 51.2 ms (20 - 60/s) or 102.4 ms (10 & 15/s) sweep time.

The waveforms presented in Figure 2 are the grand means at each presentation rate for all of the 16 subjects. Each tracing represents the average of 64,000 responses (4000 from each subject). The mean peak-to-peak amplitudes from the 16 subjects at each rate are plotted in Figure 3. The amplitude of the response is greatest with repetition rates of 40 - 45/s and smallest at the slower and faster rates. The mean amplitude at 40 and 45/s was 1.06 µV (SD = 0.29), which decreased to 0.65 (0.18) and 0.52 (0.26) µV at 10/s and 60/s, respectively. The maximum amplitude of the response occurred at 20/s in 1 subject, at 30/s in another subject, at 40/s in 5 subjects, at 45/s in 6 subjects and at 50/s in 1. These differences were not related to the gender [$F = 0.33$; $df = 1,14$; $p>0.10$] or the age [$r = 0.16$; $p>0.10$] of these adult subjects.

Insert Figures 2 and 3 about here

The responses from each subject to the stimulus presented at 40/s are presented in Figure 4. This demonstrates the high degree of similarity in response amplitude and morphology between subjects. No significant differences in the 40/s response amplitude were found between male and female subjects [$F = 1.34$; df = 1,14; $p > 0.10$]. The average amplitude at stimulus rates of 40/s was 0.97 µV for the male subjects and 1.15 µV for the female subjects. There were no significant effects of age on the 40/s response amplitude [$r = 0.10$; $p > 0.10$].

Insert Figure 4 about here

The shape of our amplitude/rate function obtained from 16 subjects is practically identical to that presented by Galambos et al. (9). It demonstrates the amplitude at 40/s to be nearly twice that recorded at 10/s. It also shows the additional peak in the amplitude function at a rate of 20/s, and depression at 25/s. These findings support the suggestion that the 40-Hz potential evolves out of the "algebraic summation of separate 40-Hz sinusoids" (9). The response can be reliably recorded from all subjects and neither gender nor age have any clear effect on the response. Our results with age are limited to young and middle-aged adults and further evaluations will be necessary to assess the response in childhood and old age.

Experiment 2: Fourier Analysis and Averaging

This experiment investigated the use of Fourier analysis to record the 40-Hz potential. We used exactly the same conditions as in Experiment 1. Fourier analysis was performed simultaneously with signal averaging in each subject. Every 50 ms the Fourier analyzer evaluated the EEG at the fundamental frequency of the stimulus repetition rate. The resultant amplitude and phase data were averaged together over the approximately 100 seconds it took to obtain an averaged evoked potential of 2000 responses (plus a few seconds depending upon the amount of artifact rejection).

The results of this experiment are shown in Figure 5 which represents the mean amplitudes obtained from averaging and from Fourier analysis in 8 subjects. While the response amplitude at each rate is somewhat greater for the signal averaged data, the shape of the Fourier analysis function is essentially the same as that obtained with signal averaging. One reason for the separation in amplitude between the two functions is the presence of high-frequency noise in the averaged response which would increase the peak-to-peak measurements and would not be present in the narrow-band Fourier analysis. A second reason is that transient responses such as wave V of the brainstem response are often superimposed on the signal-averaged waveform.

Insert Figure 5 about here

When steady state responses are obtained at different stimulus-rates, a latency can be calculated. This latency is the latency to that portion of the waveform that stays at constant phase regardless of the stimulus-rate. It can be considered the latency to the dominant component of the steady state response. The method of deriving latency from the averaged data using the technique of Diamond (5,6) is shown for one subject in Figure 6. The mean "derived" latency for the 8 subjects calculated using the Diamond technique was 33.3 ms (SD = 8.6). The "apparent latency" of the Fourier-analyzed results was calculated using the method described by Regan (18). The phase data from the Fourier analysis are plotted against repetition rate in Figure 7. The phase of the response increases linearly from 30 to 60/s. The mean apparent latency for the 8 subjects was 34.0 ms (SD = 10.8). The two methods - one a "time-difference analysis", the other a "phase-difference analysis" - thus provide essentially the same results. The resultant latency of 33 - 34 ms lies in the range of the Pa component of the 10/s transient response.

Insert Figures 6 and 7 about here

Experiment 3: Stimulus Intensity

This experiment investigated the effects of stimulus intensity on the 40-Hz potential using both signal-averaging and Fourier analysis. The 500 Hz toneburst was presented at 40/s in 10-dB steps from 90 to -10 dB nHL. There was also a control condition in which the earphone was disconnected. The order of the intensities was randomized. Behavioral threshold (SL) for the stimulus presented at 40/s was obtained using the method of limits with 5-dB steps. Replicate waveforms of 2000 averaged responses each were recorded using the 51.2 ms sweep at each intensity from 10 subjects. At the same time, the amplitude and phase of the 40-Hz fundamental in the EEG were obtained using Fourier analysis.

Figure 8 shows the effect of stimulus intensity on the amplitude of the 40-Hz potential. The results from both methods of analysis again parallel each other. The decrease in 40-Hz ERP amplitude is fairly linear down to threshold, with the mean amplitude at 90 dB nHL being 1.63 (SD=0.65) and 1.46 (SD=0.60) µV, decreasing to 0.26 (SD=0.10) and 0.16 (SD=0.11) µV at 20 dB nHL using signal averaging and Fourier analysis, respectively. These represent amplitude decreases of 20 nV per decibel. The change in amplitude was quite linear between 90 and 20 dB ($r = 0.99$ for mean data). The amplitudes obtained using signal averaging are slightly greater than those obtained using Fourier analysis for the same reasons as noted for the preceding experiment.

Insert Figure 8 about here

The noise level of the recording technique was determined in the control condition wherein the earphones were unplugged. The noise level was 0.18 (SD=0.04) µV for signal-averaging and 0.09 (SD=0.06) µV for Fourier analysis. The 40-Hz potential amplitude decreases to these noise levels at intensities below 13 (range=-10 - 40) dB for signal averaging and below 15 (range=-10 - 40) dB for Fourier analysis. These levels are 4.5 and 2.5 dB below the average behavioral thresholds (SL). This SL threshold was some 15 dB higher than the nHL threshold because there was a higher level of ambient noise in the laboratory where the evoked potentials were recorded than in the sound-attenuated chamber where the nHL was obtained.

The latency to the first vertex-positive peak of the averaged response and the phase of the 40-Hz fundamental changes with stimulus intensity. The mean latency of the averaged response for the 10 subjects was 7.61 ms at 90 dB nHL, increasing linearly to 15.46 ms at 20 dB nHL, as shown in Figure 9. A linear regression analysis performed on these data (plotted as the continuous line in Figure 8) shows a slope of 114 µs/dB increase in latency [$r = -0.79$; $p<0.0005$]. The phase data obtained using Fourier analysis were converted to milliseconds, and the change in latency from 90 dB nHL calculated (i.e. the 90 dB latency was set at zero ms). Again, the results using Fourier analysis paralleled those of averaging, with a slope of 125 us/dB obtained [$r=-0.65$; $p<0.0005$]. This linear regression is shown in the interrupted line of Figure 9.

Insert Figure 9 about here

These 40-Hz response latency changes with intensity are within the range of 100 to 200 µs/dB reported by Galambos et al. (9), but are somewhat larger than those reported for the transient responses. Thornton, Mendel and Anderson (30) reported an approximately 75 µs/dB change for the Pa potential evoked by 1000 Hz tones (data measured from figure). Wolf and Goldstein (31) reported a 95 µs/dB slope for the Pa component evoked by 500 Hz tones in neonates.

Experiment 4: The Zoom Technique

This experiment employed the zoom technique (18,19, 20,21,22,23,24) of Fourier analysis to determine the effects of stimulus rate and tonal frequency on the steady state potentials.

The zoom technique is illustrated in Figure 10. The computer continually changes some parameter of the stimulus (in our experiment, the stimulus repetition rate) and registers the amplitude and phase of the response during these changes. Whereas the method in Experiment 2 involved obtaining the amplitude/rate function using Fourier analysis at discrete 5/s steps (i.e. stimulate at 20/s for 100 seconds, calculate average amplitude and phase over this time and print out values, increase rate to 25/s, calculate and print out values, increase to 30/s, etc.), the zoom technique sweeps or "zooms" continuously in 1/s steps, calculates amplitudes and phases for each rate, averages together the measurements from several sweeps, and plots out the resultant amplitude-rate and phase-rate functions.

Insert Figure 10 about here

Six subjects participated in this study. Acoustic stimuli were the 500, 1000, 2000, and 4000 Hz tonebursts presented at 98 dB peak SPL. Each toneburst had rise and fall times of 4 ms each and a plateau duration of 2 ms. After obtaining the amplitude/rate and phase/rate functions for each subject (average of 32 sweeps) using each tonal frequency, three measurements were made: (1) the amplitude at a stimulation rate of 40/s, (2) the maximum amplitude between the rates 30 to 60/s, and (3) the rate at which the maximum amplitude was recorded. Apparent latencies to each tonal stimulus were also calculated on the phase data from 35 to 55/s, except in one subject whose phase data was only clearly linear from 35 to 44/s.

The amplitude results from the 6 subjects for the 500 Hz tone are superimposed in Figure 11. Although there is some inter-subject variability, the characteristic amplitude/rate function first demonstrated by Galambos et al. (9) can be clearly discerned. The phase vs rate data for the 6 subjects are also superimposed in Figure 11. The phase data are more consistent across subjects than are the amplitude data. As in Experiment 2, the phase of the fundamental component increases linearly with increasing stimulus presentation rate, especially after 30/s. These 500 Hz amplitude and phase results, summarized as grand means on the left of Figure 12, are similar to those from Experiments 1 (Figure 3) and 2 (Figures 5 & 6).

Insert Figure 11 about here

Table 1 summarizes the data for rate and tonal frequency obtained using the zoom technique and Figure 12 shows the grand mean amplitude/rate and phase/rate functions for the 500 and 4000 Hz tones. The decrease in amplitude with increasing tonal frequency is statistically significant at 40/s [F = 7.43; df = 3,15; p = 0.003], and at the maximum [F = 5.27; df = 3,15; p = 0.01]. The rate at which the maximum amplitude was recorded tended to increase with increasing tonal frequency, but this was not statistically significant [F = 1.85; df = 3,15; p = 0.18]. As can be seen in Figure 11, although reduced in absolute amplitude, the shape of the 4000 Hz amplitude/rate function is essentially the same as for the 500 Hz function. This was true in general for all four tonal frequencies. The apparent latency, calculated from the slopes of the phase/rate functions, decreased with increasing tonal frequency. This frequency effect approached but did not reach statistical significance [F = 4.23; df = 3,15; p = 0.024].

Insert Figure 12 about here

The decrease in amplitude with increasing tonal frequency for the 40/s response is similar to although not as large as that reported in the original study using averaging published by Galambos et al. (9). In another study, we have found the amplitude of the averaged 4000 Hz response at 70 dB nHL to be approximately half that of the 500 Hz response (27). These amplitude differences could represent, as Galambos and his colleagues have suggested, the amount of the basilar membrane which is stimulated (8,9). Similarly, the decrease in apparent latency with increasing tonal frequency could be related to the velocity of the travelling wave along the basilar membrane.

CONCLUSIONS

When auditory stimuli are presented at 40/s, a sinusoidal response at the rate of stimulation can be recorded from the human scalp. With stimuli of moderate intensity this response is easily recorded in all subjects and is quite replicable from one subject to another.

The amplitude/rate function first demonstrated by Galambos et al. (9) is a very robust phenomenon. Presentation rates of 40 - 45/s result in a steady state potential which is approximately twice as large as that recorded at 10/s. The effects of stimulus-rate are similar across the different tonal frequencies.

The 40-Hz steady state potential can be recorded to within a few dB of behavioral threshold, with an amplitude which decreases linearly down to threshold. Our results should be interpreted with caution because of the high levels of ambient noise in the laboratory. Other experiments performed in a sound-attenuated chamber indicate that the response can be recorded on average down to 15 dB nHL (27); therefore this response could be used to predict behavioral thresholds in normal hearing subjects (9,10,12,27) and in hearing-impaired patients (10,11,27). Our data reflect measurements made on adult subjects and hence the results should not be generalized to a pediatric population (29). The 40-Hz response is larger at the lower tonal frequencies. It may therefore be complementary to the auditory brainstem response which is more easily recorded with higher tonal frequencies.

Fourier analysis can be used to record the auditory steady state potentials. This technique provides essentially the same results as signal averaging. The two methods provide nearly identical amplitude/rate, amplitude/intensity, and latency/intensity functions. Either or both of these techniques may be used, therefore, to record the 40-Hz steady state potential. Fourier analysis, however, does not require the purchase of the expensive equipment used for signal averaging. The analyzer can be built using a few integrated circuits (22) and the calculations can be done by integrated circuit devices or by an inexpensive microcomputer. Furthermore, the Fourier analysis of steady state potentials does not entail some of the common problems associated with signal averaging: no decision regarding which "peak" is at which latency need be made; no baseline determination is required; and no decision whether a peak exists or not must be made. Instead, Fourier analysis provides objective measures of amplitude and phase (22). Fourier analysis probably also has an advantage in speed. Further evaluation of the reliability of the recordings obtained using signal-averaging and Fourier analysis is needed. Our initial impression, however, is that the technique provides reliable measures in less than one quarter of the time required by averaging. In the fourth exeriment, for example, the time required by the zoom technique was about one fifth what would have been necessary using the averaging technique of Experiment

1, and the data appeared equally reliable. Fourier analysis and the zoom technique can be used with parameters other than stimulus presentation rate. The most obvious parameter for audiometry is stimulus intensity, which could be swept from supra- to sub-threshold levels in order to obtain auditory thresholds. Other frequency-based techniques can also be used to assess the 40-Hz potential. Martin and Hayes (12), for example, have evaluated the Fast Fourier Transform of the averaged 40-Hz response in order to obtain auditory thresholds.

Considerably more research on the 40-Hz steady state potential is needed to be done. Little is known of its cerebral origin. Galambos has suggested it may arise from polysensory extralemniscal areas such as the brainstem and/or thalamic reticular formation (7,8); however, no studies have directly investigated this possibility. The relationship between the transient response and the 40-Hz response is not clear. Is the 40-Hz response simply a superimposition of the negative-positive peaks of the transient response - and hence similarly generated - or is it different? What is the relationship between the auditory 40-Hz response to similar responses in other modalities (7,8) and to other 40-Hz phenomena that can be recorded from the human scalp (1,26)? Another unknown and possible problem for the 40-Hz potential is the effect of sleep and/or sedation on the response. It has been pointed out that the 40-Hz EP has approximately half its waking amplitude during sleep (2,3,7, 10a). The effects of sleep on the transient response are controversial, with some studies reporting little or no effect (13,15) while others have indicated an effect (2,3,14). These effects may have important implications for the clinical utility of the 40-Hz potential. Finally, there are limited data available on the frequency-specificity of the 40-Hz response (10b). This is particularly important if the response is to be used in objective audiometry.

In conclusion, the results of these experiments indicate the 40-Hz potential to be a robust response which can be evoked by tones of low and high frequency presented at high and low intensities. Its steady-state nature allows the use of simple, inexpensive recording techniques such as Fourier analysis. Clearly, there is a promising future for the auditory steady state responses in evoked potential audiometry.

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TABLE 1. Summary of Zoom Technique Results (N=6).

Frequency (Hz)	Amplitude (µV) 40/s	Amplitude (µV) Peak	Rate at Peak(/s)	Apparent Latency(ms)
500	1.12	1.42	40	29.3
1000	0.91	1.34	43	25.3
2000	0.89	1.30	44	20.3
4000	0.81	1.11	46	20.3
	$p<0.01$	$p=0.01$	NS	$p<0.05$

FIGURES

Figure 1. Principle of the analog Fourier analyzer.
The stimulus generator (S) is triggered by an oscillator (O) at the repetition rate (FHz). The subject's EEG is amplified (A) while he receives the auditory stimulus, and is fed into the Fourier analyzer to be multiplied (M) by the sine and the cosine of the stimulus repetition frequency. These multiplications convert the FHz component into a steady d.c. output; all other frequency components are converted to a.c. output. The a.c. outputs are removed with a low-pass filter (F). The remaining d.c. outputs (x,y) are used to calculate the amplitude and phase of the FHz component using the formulae at the bottom of this figure.

Figure 2. The effects of stimulus presentation rate on the Middle Latency Responses. The waveforms are the grand means from the 16 subjects, each representing 64,000 responses (4000 per subject) to the 500 Hz tones presented at 60 dB nHL (re. a 10/s presentation rate). The recordings were taken from vertex to the mastoid ipsilateral to the ear stimulated. Negativity at the vertex is plotted as an upward deflection. Wave V of the brainstem response and waves Na and Pa of the transient middle latency response are clearly visible in the 10/s response. Around 40-45/s, a large amplitude sinusoidal wave - the 40-Hz ERP - of the same frequency is recorded.

Figure 3. The amplitude/rate function of the middle latency responses. The mean peak-to-peak amplitudes from the 16 subjects in response to the 60 dB nHL 500 Hz tone are shown above. This

function replicates that of Galambos and coworkers (9), with peak amplitudes around 40 - 45/s, and minima at the slower and faster rates.

Figure 4. The 40-Hz steady state potential. Top: Superimposition of the responses from 16 subjects, demonstrating the similarity of the 40-Hz ERP amplitude and morphology between subjects. The recordings were taken from vertex to the mastoid ipsilateral to the ear stimulated. Negativity at the vertex is plotted as an upward deflection. Bottom: Diagram of the 500 Hz stimulus which occurred twice in each 51.2 ms sweep.

Figure 5. Fourier analysis and averaging. The responses to the 60 dB nHL 500 Hz tones presented in steps of 5/s were simultaneously recorded using both signal averaging and Fourier analysis. The Fourier analyzer always evaluated the EEG at the frequency of the stimulation rate. The average data from 8 subjects are plotted in this figure, with the averaging results plotted as a continuous line and the Fourier analysis as an interrupted line. Both methods provide essentially the same results, with the maxima at 40 - 45/s.

Figure 6. The Diamond (5,6) technique of deriving the latency of a steady state response from data obtained using signal averaging. The left of this figure demonstrates how lines can be drawn connecting particular peaks in each waveform recorded at different interstimulus intervals (ISI). Some components change in latency more than others, while one usually shows little or no latency change with rate. The latter can be considered the dominant component in the steady state response. The latencies of the 4

components in this subject's responses are plotted on the right, and the linear regressions calculated using these points are drawn for each component. The latency intercepts of these regressions are all within 2.5 ms of each other. The mean of these intercepts - 43.99 ms - is the "derived latency" (the Regan "apparent latency" for this subject was 43.16 ms). The mean of 2 latency intercepts from 2 regressions from each subject was used for the calculation of derived latency in Experiment 2.

Figure 7. Phase of the steady state response. This figure shows the phase vs rate functions - 30 to 60/s - for each of the 8 subjects, obtained using the Fourier analyzer. The analyzer always evaluated the EEG at the frequency of stimulation. Phase increases linearly from 30 to 60/s, and is fairly replicable from subject to subject. Apparent latency for each subject's responses was calculated on the phase data from 35 - 55/s.

Figure 8. The effects of stimulus intensity on the amplitude of the 40-Hz steady state potential. The mean averaging and Fourier analysis results from 10 subjects are plotted using continuous and interrupted lines, respectively. The mean noise levels were obtained in a condition in which the earphone was unplugged. The mean behavioral threshold is marked by "SL". The 40-Hz potential amplitude decreases linearly down to behavioral threshold, with both Fourier analysis and averaging providing the same results.

Figure 9. The effects of stimulus intensity on the latency of the 40-Hz steady state potential. The latency to the first positive peak in the averaged response is plotted using a continuous line. The phase-converted-to-latency from Fourier analysis is plotted

using interrupted lines. Dividing the phase by (40 X 360°) converted this measure to latency (seconds). The Fourier analysis data are plotted with the 90 dB latency arbitrarily set to zero. The latency of the 40-Hz potential increases linearly with decreasing stimulus intensity, with both methods of analysis providing similar functions (114 and 125 µs/dB for averaging and Fourier analysis, respectively).

Figure 10. The zoom technique. The computer sweeps or "zooms" a stimulus parameter - in this case, rate - and calculates the amplitude and phase of the EEG activity at the fundamental frequency (the repetition rate) as it zooms the stimulus. Following this the data is stored on disk to be averaged and plotted. The phase data are plotted such that values reset to zero every 360° (e.g. 540° is plotted as 180°). This technique has the computer carrying-out most of the recording and analysis functions, with little intervention required.

Figure 11. Amplitude/rate and phase/rate functions for the auditory steady state potentials obtained using the zoom technique. This figure shows the superimposed data from six subjects. The stimulus was the 500 Hz tone presented at 98 dB peak SPL. The characteristic amplitude function with maxima around 40 - 45/s can be discerned, as well as the phase increase with increasing rate.

Figure 12. Grand mean 500 and 4000 Hz amplitude/rate and phase/rate functions. These functions, recorded using the zoom technique, are the mean data from six subjects. The larger maxima at 40 - 45/s and the smaller 20/s maxima are similar to data obtained in Experiments 1 and 2. The 4000 Hz function has the same general

shape as the 500 Hz function, although it is of somewhat smaller amplitude. The phase data indicate that phase increases with increasing stimulus rate, with this increase being more linear after 30/s. The slope of the phase graph is lower for the 4000 Hz tone than for the 500 Hz tone.

Figure 1

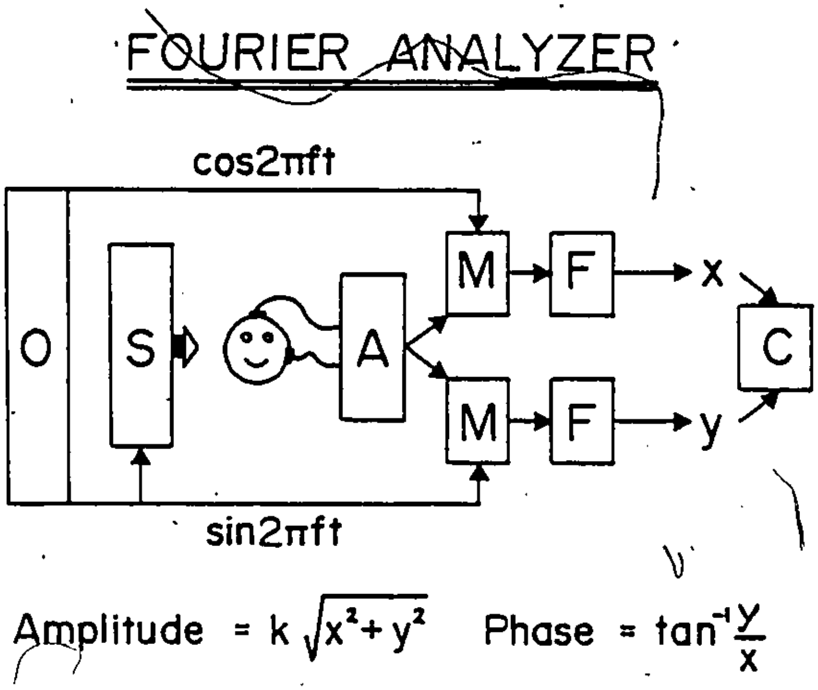

FOURIER ANALYZER
cos2πft
O
S
A
M
F
x
C
M
F
y
sin2πft
Amplitude = k √(x² + y²)
Phase = tan⁻¹ y/x

Figure 2

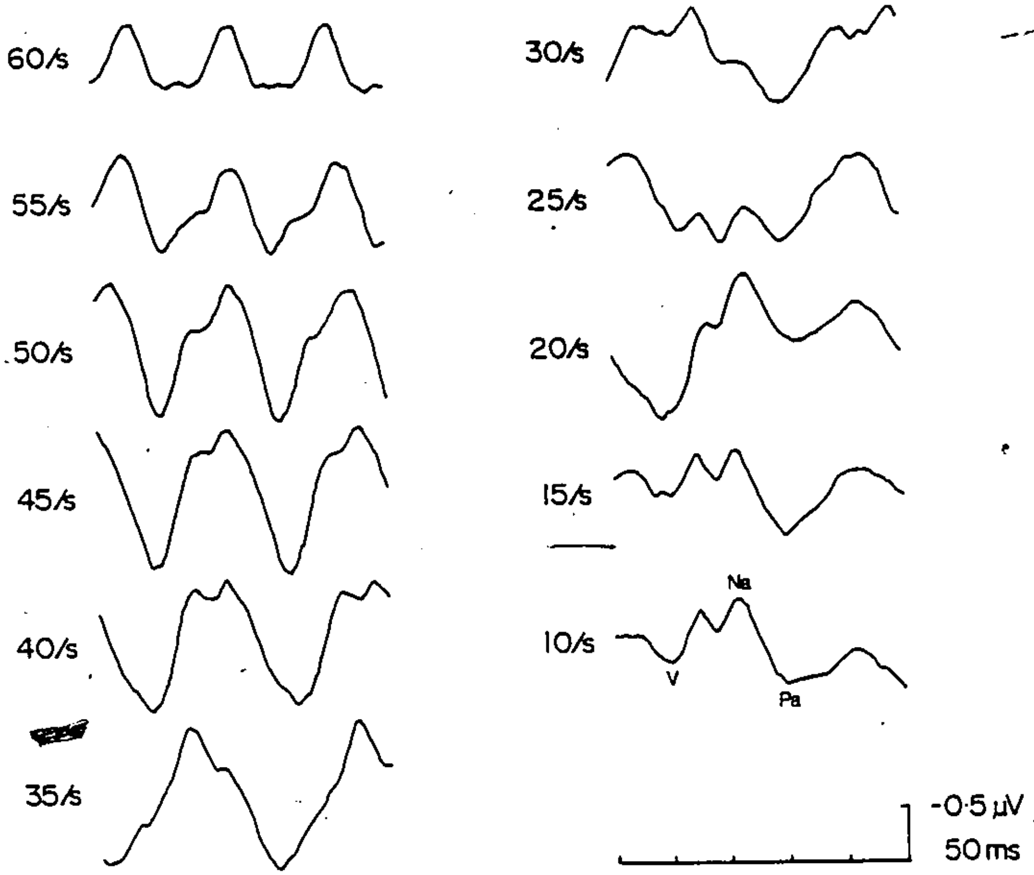


Figure 3

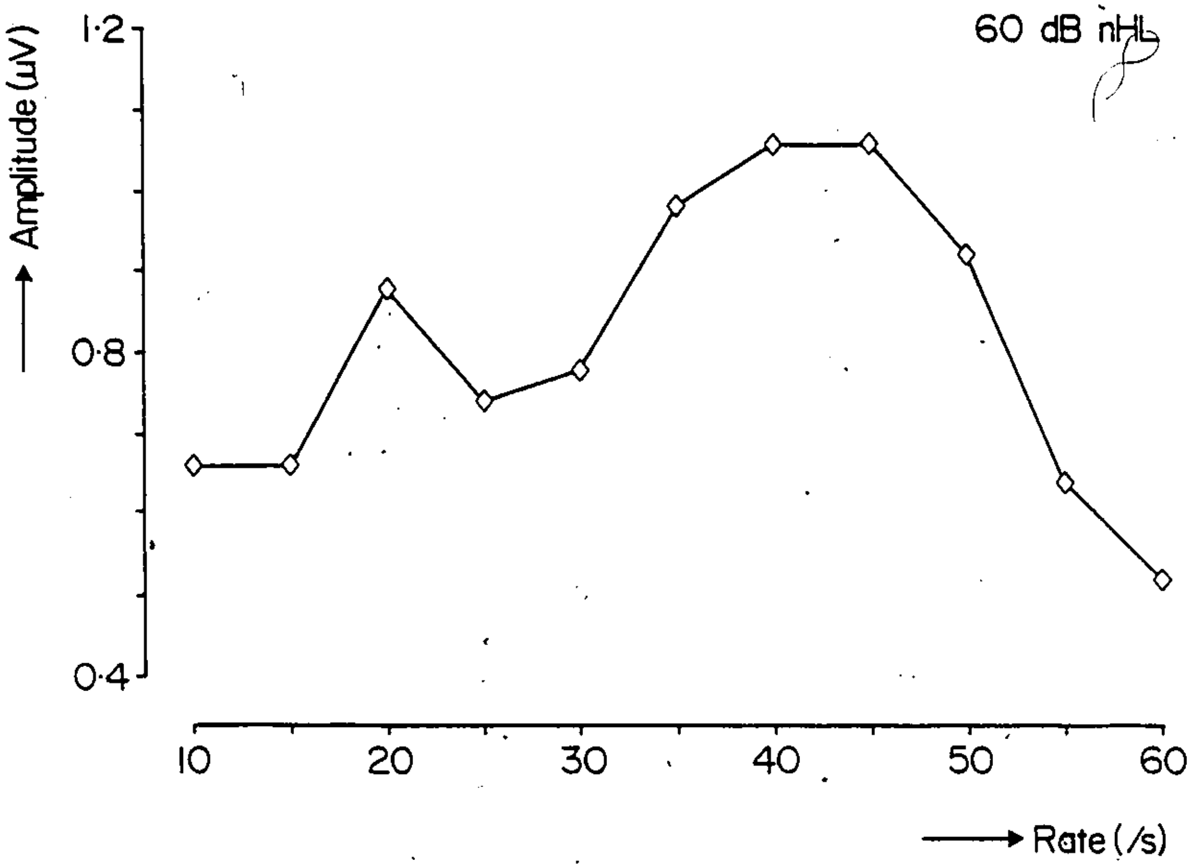


Figure 4

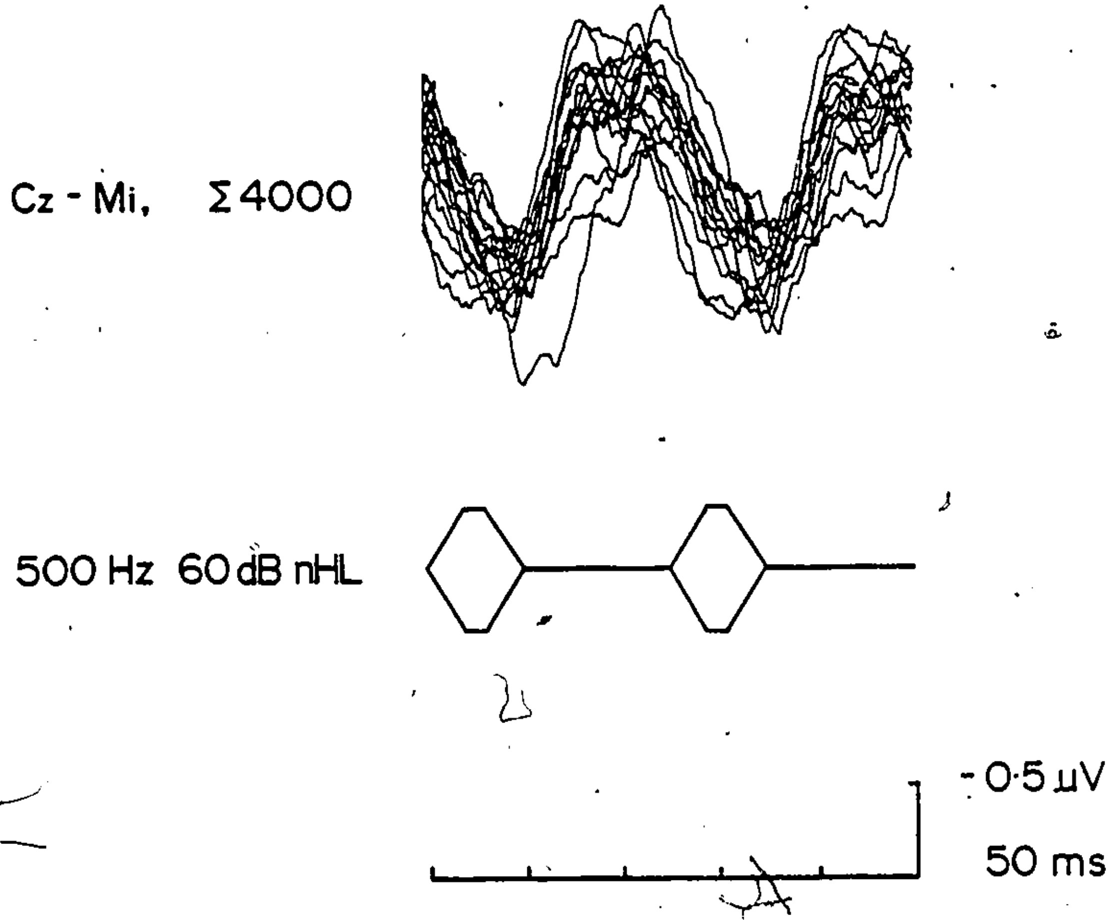


Figure 5

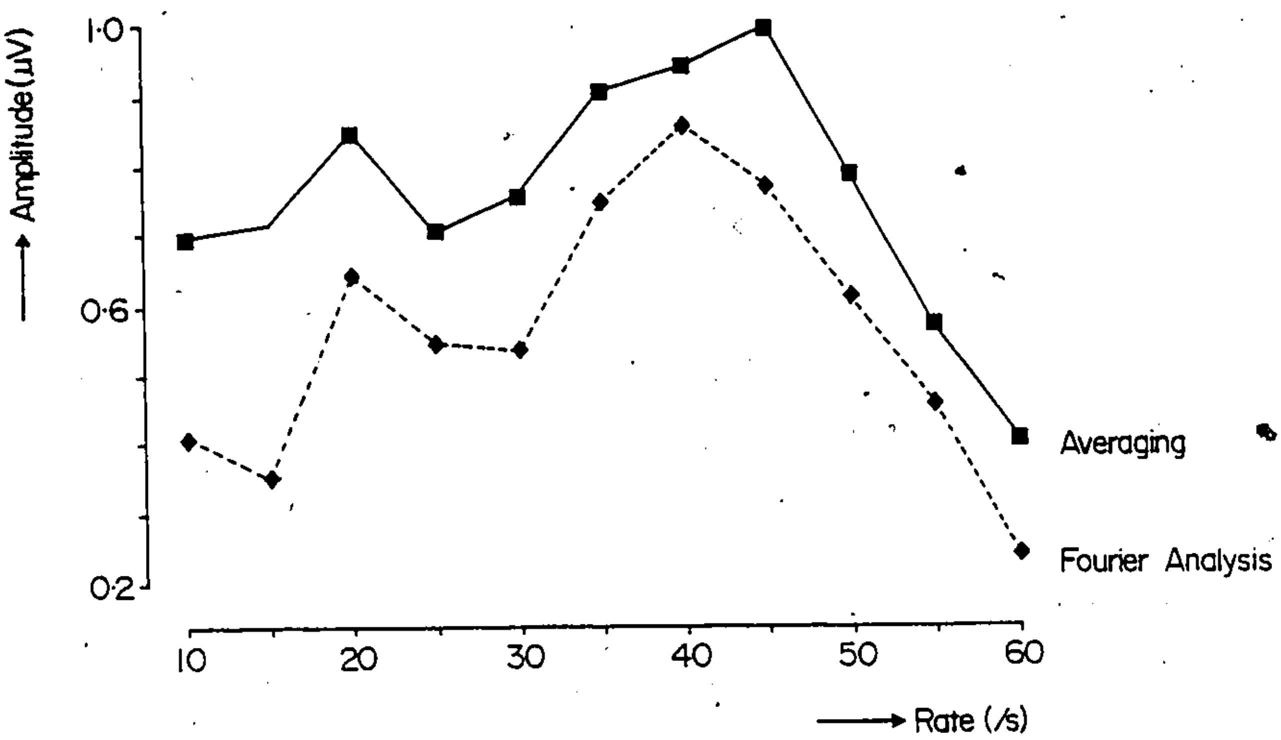

1·0
0·6
0·2
→ Amplitude (µV)
10
20
30
40
50
60
→ Rate (/s)
Averaging
Fourier Analysis

Figure 6

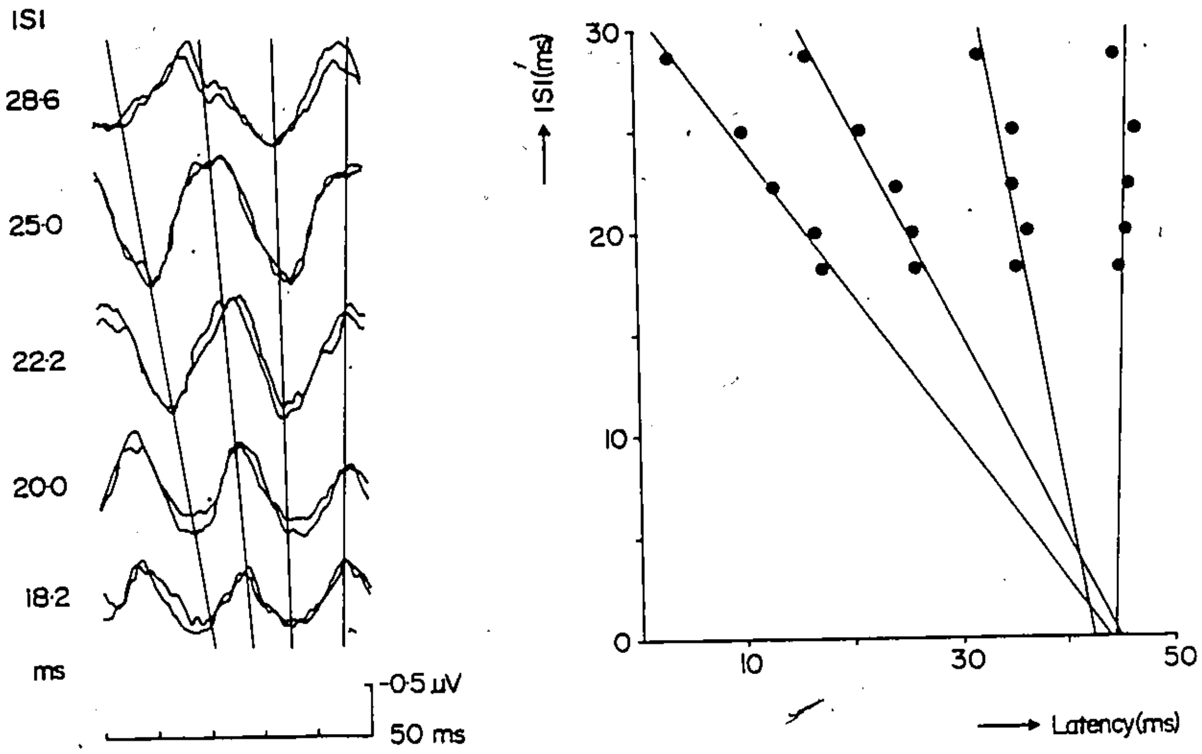

ISI
28·6
25·0
22·2
20·0
18·2
ms
-0·5 µV
50 ms
30
20
10
0
→ ISI(ms)
10
30
50
→ Latency(ms)

Figure 7

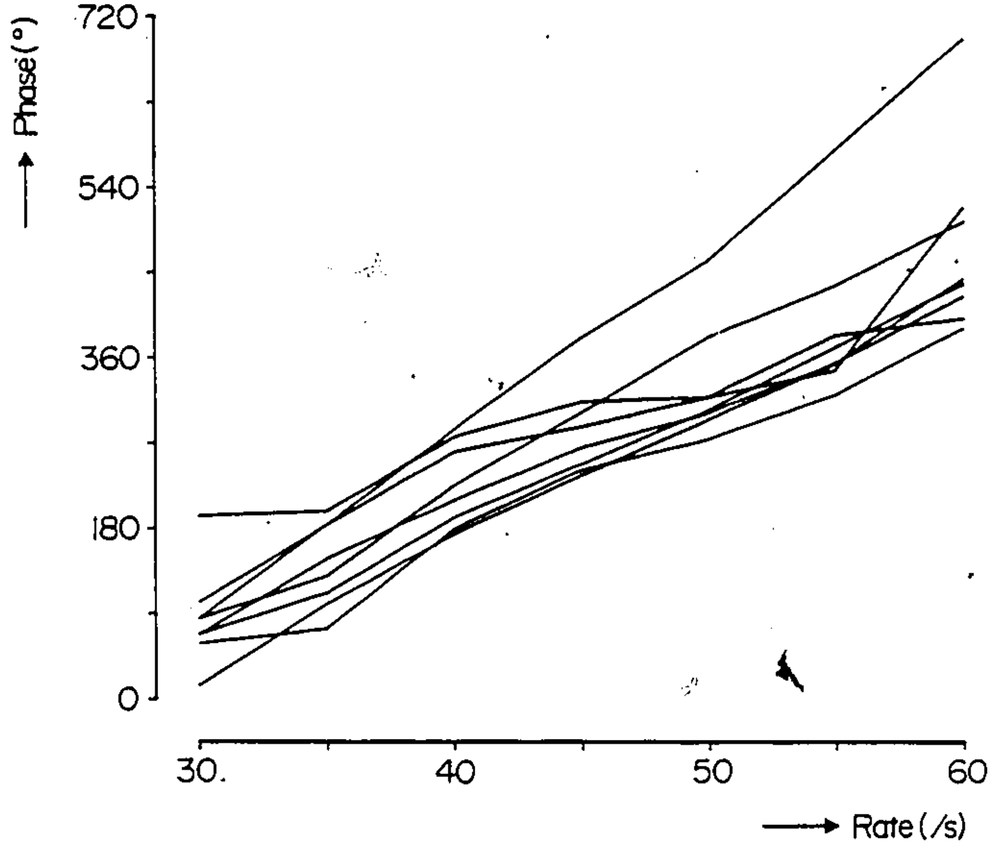


Figure 8

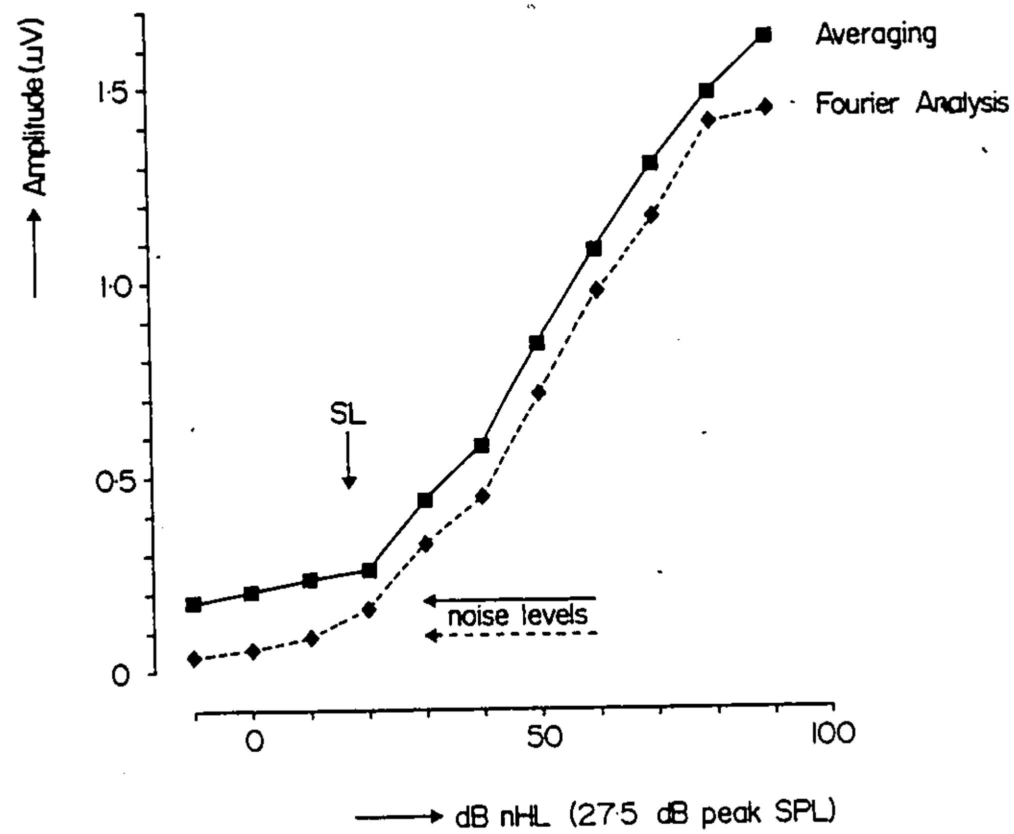

Amplitude (µV)
1·5
1·0
0·5
0
SL
noise levels
Averaging
Fourier Analysis
0
50
100
dB nHL (27·5 dB peak SPL)

Figure 9

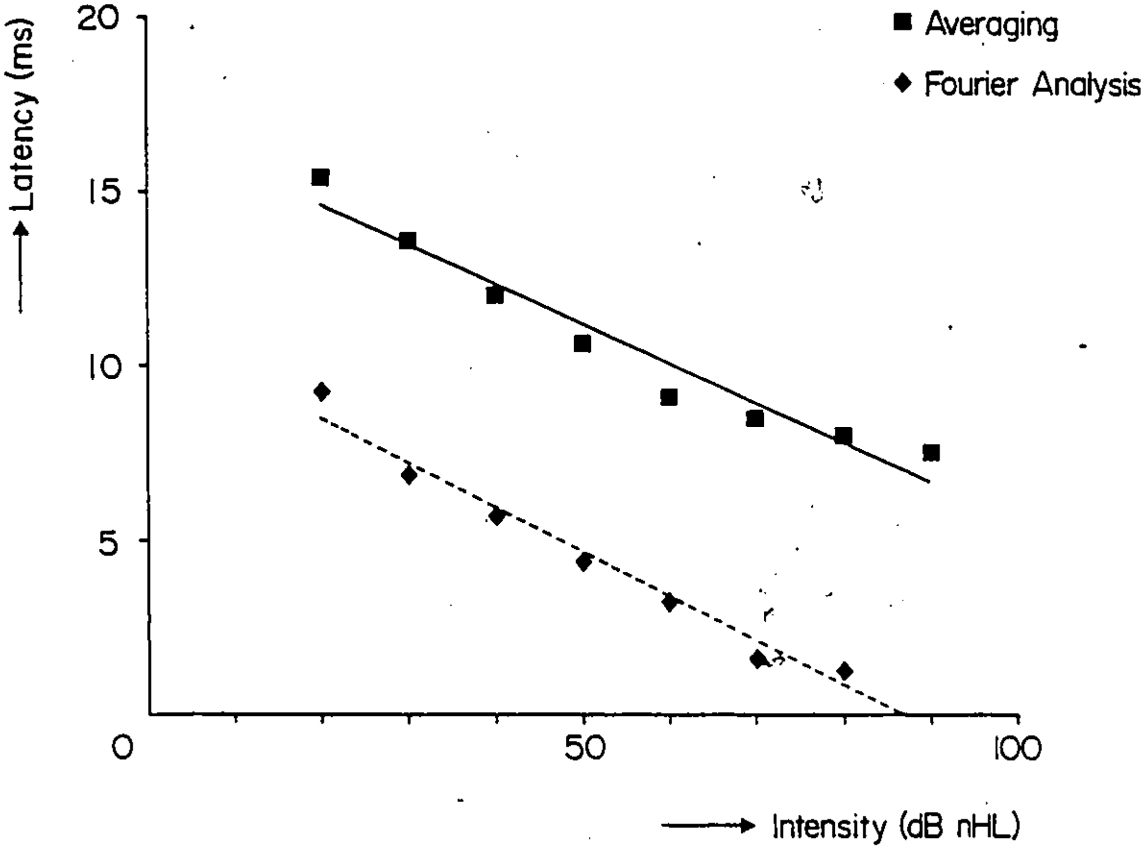

■ Averaging
◆ Fourier Analysis
20
15
10
5
0
50
100
→ Latency (ms)
→ Intensity (dB nHL)

Figure 10

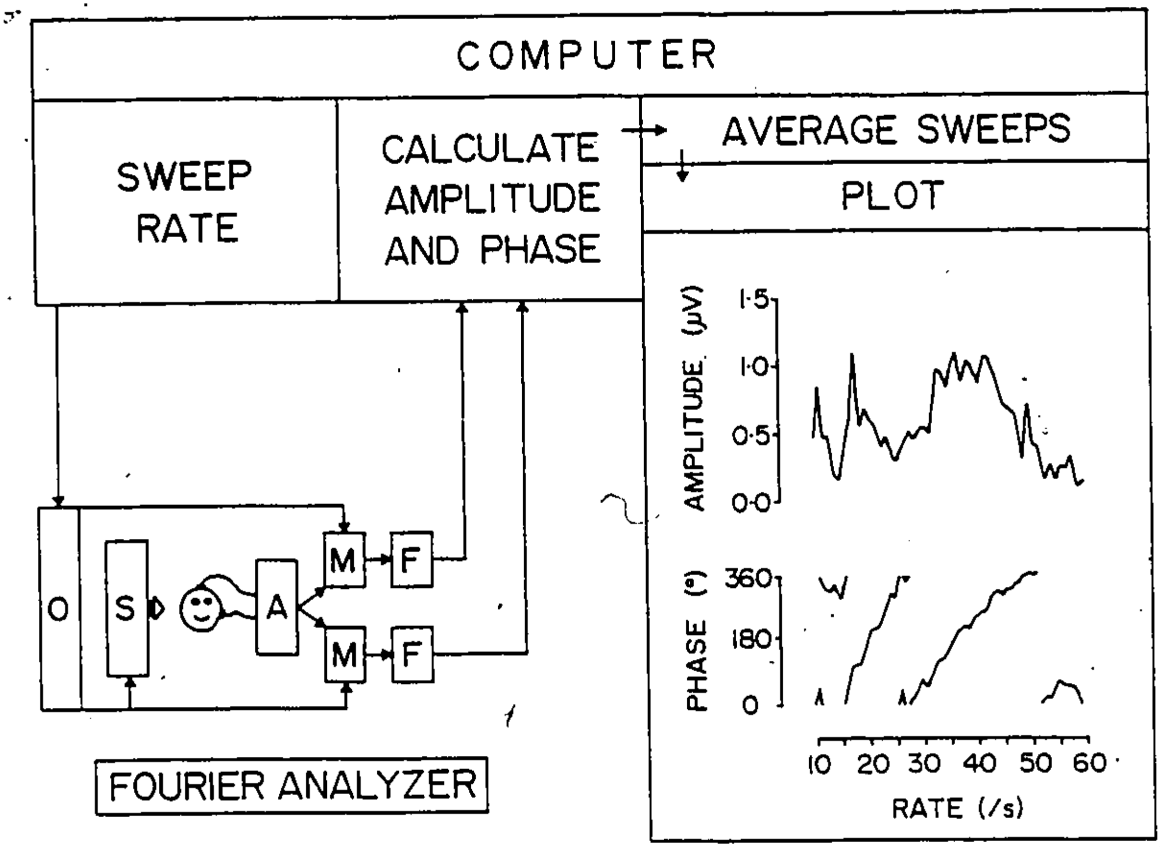

COMPUTER
SWEEP RATE
CALCULATE AMPLITUDE AND PHASE
AVERAGE SWEEPS
PLOT
AMPLITUDE (µV)
1·5
1·0
0·5
0·0
PHASE (°)
360
180
0
10
20
30
40
50
60
RATE (/s)
O
S
A
M
F
M
F
FOURIER ANALYZER

Figure 11

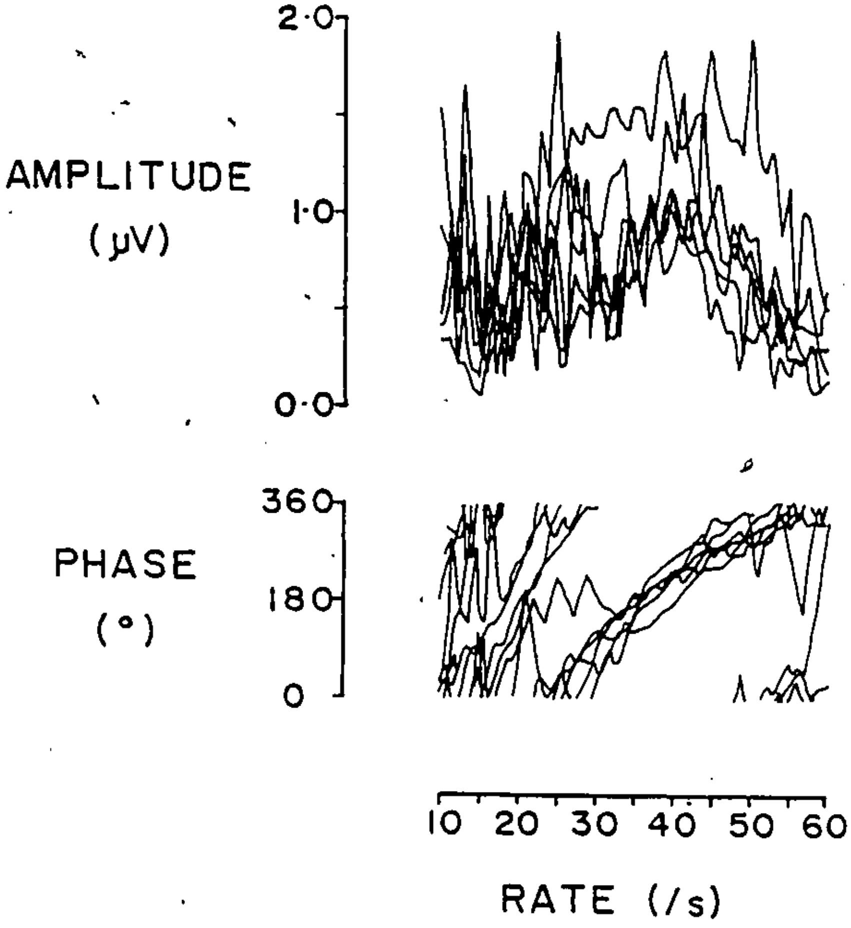
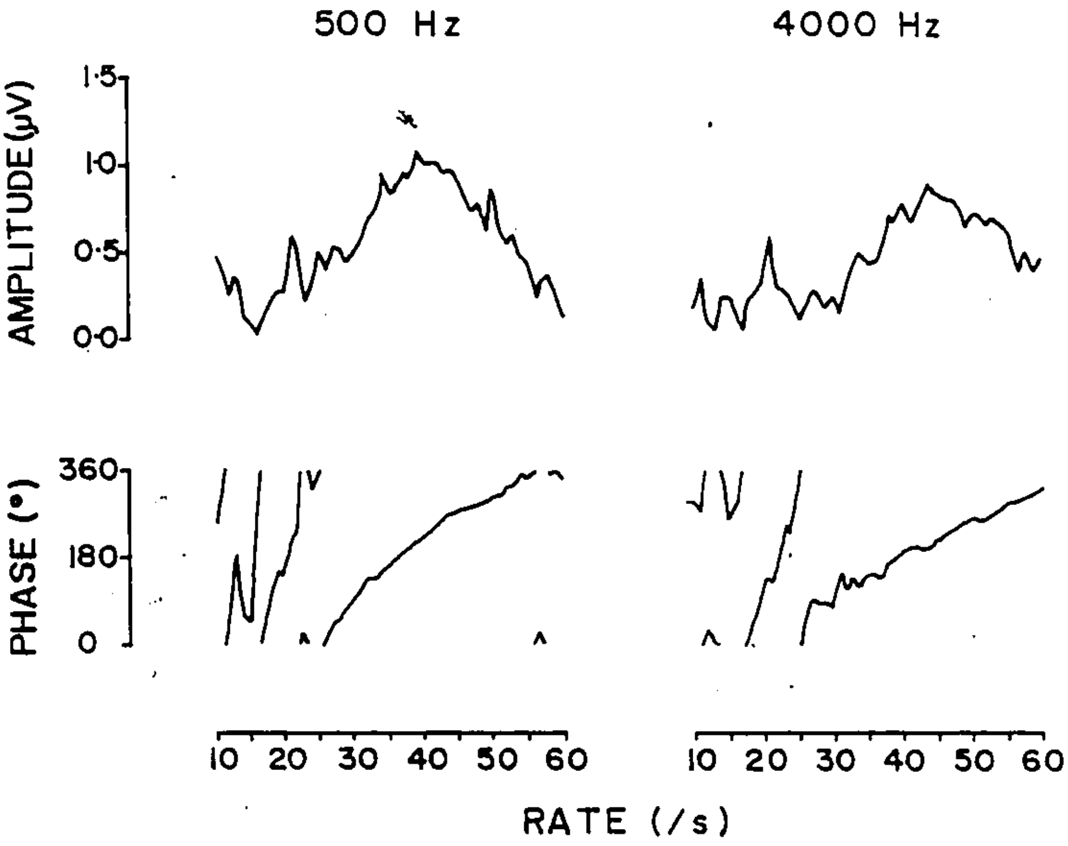


Figure 12


500 Hz
4000 Hz
AMPLITUDE (μV)
1·5
1·0
0·5
0·0
PHASE (°)
360
180
0
10
20
30
40
50
60
RATE (/s)

Estimation of Threshold in Normal and Hearing-Impaired Individuals using Auditory Evoked Potentials

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Abstract

Eight auditory evoked potential (EP) techniques for frequency-specific objective audiometry were evaluated in ten normal-hearing and ten hearing-impaired subjects. The eight EP techniques were the Slow Response, the Transient Middle Latency Response (MLR), the 40-Hz Steady State Potential, and five brainstem response techniques (Derived Responses, Clicks in Notched Noise, unmasked Tone responses, Tones in Notched Noise, and Tones in White Noise). All EP tests were recorded in each subject to obtain threshold information at 500, 1000, 2000, and 4000 Hz. Each technique was evaluated by considering (a) the accuracy of pure tone threshold prediction, (b) the inter-subject variability, (c) the response clarity, and (d) the inter-rater reliability. The Derived Response and the Clicks in Notched Noise Techniques require caution because of the high intensities required to mask the clicks, and give responses that are small and variable. The variability and lack of clarity of the Transient Middle Latency Responses indicate that they also are not very useful for objective audiometry. The Slow Responses and the 40-Hz Steady State Potential give intermediate results but the auditory brainstem responses to tonal stimuli (masked and unmasked) show the best results. On average, detectable responses were recordable to low- and high-frequency tones within 10 dB of pure tone behavioral thresholds when recording the ABR to tones. Noise masking of the tones improved threshold prediction when steep high-frequency hearing losses were present.

The use of a 40/s stimulus presentation rate for the tones combines the 40-Hz response with the brainstem responses, aiding response identification at low intensities, particularly for the low-frequency stimuli.

Introduction

Evoked potential (EP) audiometry measures a subject's sensitivity to sound by recording the electrical responses of the cochlea or brain. EP audiometry is considered "objective" since it does not require any behavioral response from the subject. Objective audiometry is required for testing individuals in whom the threshold-information obtained using behavioral audiometry is incomplete or unreliable. Patients commonly requiring objective audiometry are the very young, the mentally handicapped, the emotionally disturbed, and the unconscious. It is with the first group of individuals that EP audiometry has its most important use: the early identification of hearing loss in infants (Downs, 1982; Galambos, 1982; Gerber & Mencher, 1978; Mencher & Gerber, 1981).

The auditory evoked potentials which can be recorded from the human scalp can be classified as transient, sustained, and steady state responses (Davis, 1976; Picton, Woods, Baribeau-Bräun, & Healey, 1977; Picton & Fitzgerald, 1983; Starr & Don, in press). A transient EP is elicited by a change in the auditory stimulus, such as the onset or offset of a tone, or a change in its frequency or intensity. They are presently widely used in the clinic for objective audiometry. Sustained responses are elicited by the continuation of the stimulus. They tend to be smaller in amplitude than the transient EP to the same stimulus (Picton, Stapells & Campbell, 1981; Picton et al., 1977), and are therefore probably not very helpful for threshold prediction

(Davis, 1981). Steady state potentials are elicited by stimuli presented at a sufficiently high rate to cause an overlapping of the responses to successive stimuli. This results in a periodic response with a constant phase relationship to the repeating stimulus. The auditory steady state responses have been studied as a possible technique for objective audiometry (Galambos, Makeig & Talmachoff, 1981; Stapells, Linden, Suffield, Hamel & Picton, in press-a).

Transient evoked potentials are usually classified into three main divisions on the basis of the post-stimulus latencies of their various components. The "fast" responses (1 - 20 ms) represent activity from the auditory nerve and brainstem structures; the "middle" latency responses (10 - 50 ms) may represent activity from the brainstem, thalamus and primary auditory cortex; and the "slow" components (50 - 250 ms) representing activity in the primary auditory cortex, the temporal auditory association cortex, and the frontal association areas (Davis, 1976; Picton, Hillyard, Krausz & Galambos, 1974; Starr & Don, in press).

Slow Responses. The Slow Responses were the first to be used in objective audiometry (Davis, 1976), and as recently as 1976 these responses were still the most commonly used EP component for audiometry (Picton et al., 1977). The Slow Response includes the components P1, N1, P2, and N2, with the N1-P2 complex having latencies between 100 and 200 ms at higher intensities being the clearest part of the response in an awake subject. This response can be elicited by low- and high-frequency tonal stimuli with rise-times and plateau-durations of around 20 ms each. Such stimuli provide reasonably good frequency-specificity (Davis, 1976; Gibson, 1978; Mendel, 1977; Onishi & Davis, 1968; Picton et al., 1977). The amplitude of the response decreases as the interstimulus interval (ISI) is decreased below 10 seconds. An ISI of 1 - 2 seconds is the most efficient presentation rate, providing an optimal compromise between response amplitude and recording time (Davis, 1976; Picton et al., 1977).

Response thresholds for the slow potentials are usually reported as being within 10 - 20 dB of normal hearing thresholds (nHL) in awake and cooperative adults (Davis, 1976; Gibson, 1978; Mendel, 1977; Picton et al., 1977). The estimation of audiometric threshold using this response, however, is not without problems. Rose, Keating, Hedgelock, Miller, and Schreurs (1972) report occasional discrepancies between slow EP thresholds and behavioral thresholds of more than 60 dB; Mendel, Hosick, Windman, Davis, Hirsh and Dinges (1975) report a mean slow response threshold in awake adults of 27 dB SL, with a range of 10 to 45 dB SL; Salomon, Parving, and Elberling (1981) report differences between electrocochleographic and slow response thresholds of greater than 25 dB in 41 of 83 cases. These problems may be related to fluctuations of the subject's level of arousal and attention (Picton et al., 1977). Since it is difficult to control these parameters in infants and young children, there are problems when the Slow Responses are recorded from those individuals who need EP audiometry most. This has prompted Davis (1976) and Gibson (1978) to suggest that the Slow EPs are not appropriate for the testing of children.

The above problems notwithstanding, the Slow Responses offer the best choice for determining frequency-specific thresholds because of the long duration of the tonal stimuli used. Recording these potentials also allows an evaluation of the higher levels of the auditory system.

Middle Latency Response. The Middle Latency Response (MLR) is less sensitive than the Slow Responses to changes in attention (Picton & Hillyard, 1974). There exists, however, some controversy as to what degree the MLR is affected by sleep: Mendel and Goldstein (1969) and Mendel and Kupperman (1974) report no change in the MLR with sleep, while Mendel and Goldstein (1971) show large decreases in amplitude during sleep, component Pa decreasing about 40% from waking to Stage 3 sleep. Recent investigations have subsequently replicated these 40 - 50% amplitude decrements (Brown, 1982; Brown & Shallop, 1982). However, Picton and Smith (1978) suggested that lower thresholds may be obtained using the MLR during sleep because of the lower background noise levels (cf. Mendel & Goldstein, 1971). The MLR appears to be relatively insensitive to mild sedation with chloral hydrate or diazepam (Mendel, 1980; Özdamar & Kraus, 1983).

The vertex-positive component occurring around 30 ms -- Pa -- is the most stable of the MLR components (Davis, 1976; Gibson, 1978; Mendel, 1980), and its amplitude measured from the preceding negative wave (Na) is the best measure for identifying the MLR response (Goldstein & Rodman, 1967). The response is best elicited by click stimuli (Picton et al., 1977), but tonal stimuli may also be used. Stimulus rise times up to 5 ms may be used without significantly reducing the amplitude of Pa (Beiter & Hogan, 1973; Vivion, Hirsch, Frye-Osier & Goldstein, 1980), while plateau durations of greater than 5 ms have little effect on response amplitude (Lane, Kupperman & Goldstein, 1971; Skinner & Antinoro, 1971). The usual rate of stimulus presentation has been around 10/s (Davis, 1976; Mendel, 1977; Picton et al., 1977).

Controversy presently surrounds the filtering of the EEG when recording the MLR. Most researchers have used high-pass filter settings of 10 - 30 Hz and low pass settings of 100 - 200 Hz, even though such settings are known to cause distortions of the MLR waveform (Lane, Mendel, Kupperman, Vivion, Buchanan & Goldstein, 1974). High pass analog filtering at 30 Hz has been shown to result in the artefactual enhancement of some of the MLR components (Kileny, 1983; Scherg, 1982), especially when using filters with steep rolloff slopes. Suzuki, Kobayashi, and Hirabayashi (1983) report, however, that most of the inter- and intra-subject variability seen with the MLR disappears when the EEG is digitally-filtered such that all frequencies below 30 Hz are excluded. It appears that the best compromise when using an analog filter is for a wide-band (eg. 10-1500 Hz) recording (Scherg, 1982).

A wide variety of MLR response thresholds have been reported. Proponents of this technique, such as Mendel and his associates, report thresholds of 10 to 20 dB above behavioral thresholds using clicks (Musiek & Guerkink, 1981; Özdamar & Kraus, 1983) or tonal stimuli (Brown & Chambers, 1983; Goldstein & Rodman, 1967; Mendel, 1977; Mendel et al., 1975; Vivion, Wolf, Goldstein, Hirsch & McFarland, 1979). Others, however, have reported great variability in response threshold and waveform morphology. Lane, Kupperman, and Goldstein (1971) found no MLR recordable to a 50 dB SL 1000 Hz tone in 40% of their subjects. Musiek and Guerkink (1981) and Özdamar and Kraus (1983) both report MLR latencies and amplitudes to be considerably more variable than those seen with the auditory brainstem response (ABR).

The MLR in normal young children may be variable or non-existent (Davis, 1976; Engel, 1971; Hirabayashi, 1979; Horiuchi, 1978; Izumi, 1980; Okitsu, Kawamato & Hirose, 1980). On the other hand, there have been several studies which have successfully-recorded MLRs in young children and neonates (McRandle, Smith & Goldstein, 1974; Mendel, Adkinson & Harker, 1977; Suzuki, Hirabayashi, and Kobayashi, 1983; Tapia, Olaizola & Garzon, 1983; Wolf & Goldstein, 1978, 1980). Suzuki et al. digitally-filtered the EEG of children and reported that the detectability of Pa is considerably decreased when high-pass filter settings either higher or lower than 20 Hz are used. They found that wide-band recording of the MLR in children resulted in a lack of stability and increased variability of this response; considerable improvement was seen when the MLR was digitally high-pass filtered at 20 Hz. These researchers concluded that "the unstable responses in young children were mainly caused by low-frequency brain activities below 20 Hz" (Suzuki, Hirabayashi, & Kobayashi, 1983).

The preceding discussion indicates the controversy concerning the usefulness of the middle latency response. This response's main advantage over the slow response is that it is less affected by alterations in psychological and physiological states; its primary advantage over the auditory brainstem responses is the fact that it can be evoked by tones with longer rise-times and therefore greater frequency-specificity. The major drawback of the response is the difficulty in distinguishing it from background noise.

Auditory Brainstem Response. The auditory brainstem response (ABR) has taken over the distinction as being the most widely used EP technique for objective audiometry (Davis, 1981). The components of this response are not significantly altered by changes in attention (Picton & Hillyard, 1974; Picton et al., 1981; Woods & Hillyard, 1978) and are unaffected by sleep (Amadeo & Shagass, 1973; Campbell & Bartoli, 1983). The ABR is relatively insensitive to sedation with chloral hydrate or diazepam (Stockard, Stockard & Sharbrough, 1980), or anesthesia with barbiturates or nitrous oxide and halothane (Goff, Allison, Fisher & Conte, 1977; Sanders, Duncan & McCullough, 1979). The small amplitude of the brainstem potentials requires averaging several thousand responses (Picton et al., 1981). This is compensated by the relative insensitivity of wave V to high rates of stimulus presentation which allows rates of up to 80/s to be used (Picton et al., 1981). Hyde and Blair (1981) have suggested a stimulus presentation rate of 40/s to be the most efficient.

The ABR can be consistently recorded in neonates and older infants in response to clicks (Cone, 1979; Cox, Hack & Metz, 1981; Despland & Galambos, 1980; Durieux-Smith, Edwards, Hyde, Jacobson, Kileny, Picton and Sanders, in press; Galambos & Despland, 1980; Galambos & Hecox, 1978; Galambos, Hicks & Wilson, 1982; Hecox & Galambos, 1974; Salamy & McKean, 1976; Salamy, McKean, Pettet & Mendelson, 1978; Schulman-Galambos & Galambos, 1975, 1979; Starr, Amlie, Martin & Sanders, 1977; Stockard, Stockard & Coen, 1983) and tones (Cone, 1979; Durieux-Smith et al., in press; Kobayashi, Hirabayashi, Takagi & Suzuki, 1983; Stockard et al., 1983).

The auditory brainstem response thus appears to be the ideal EP measure for objective audiometry. The use of auditory brainstem responses for the prediction of threshold is not, however, without its drawbacks. The major problem is poor frequency-specificity of the stimuli, especially at low frequencies. The optimal stimulus for the ABR is a click, but since this is a broadband stimulus it provides only a rough idea of auditory sensitivity. Screening programs relying upon click-evoked ABRs could miss individuals with hearing losses restricted to particular frequencies. Furthermore, residual low-frequency sensitivity present in a patient with severe high-frequency hearing loss may not be detected by ABR audiometry using clicks. Attempts have been made to predict the shape of an individual's audiogram, and the site of the pathology, using the wave V latency-intensity function, but these techniques have had only limited success (Gorga, Worthington, Reiland, Beauchaine and Goldgar, 1983; Picton and Smith, 1978; Picton et al., 1977).

Numerous investigators have employed "filtered clicks" or short-duration tones in an attempt to obtain frequency-specific thresholds (see Picton et al., 1981). The amplitude of the ABR falls off dramatically when rise-times greater than 5 ms are used (Kodera, Hink, Yamada & Suzuki, 1979; Stapells & Picton, 1981). Davis (1976) has recommended the use of tonal stimuli having rise and fall times each equal to two cycles of the stimulus, and a plateau equal to one cycle. This "Davis 2-1-2 tonepip" is an approximation of the logon signal described by Gabor (1947) as the optimal compromise between time and frequency.

The effects of stimulus frequency on the tone ABR are complex. High-frequency Davis tonepips elicit brainstem responses which are similar to those evoked by clicks (Terkildsen, Osterhammel & Huis in't Veld, 1973, 1975a, 1975b). Early research found that responses to low-frequency stimuli, however, were difficult to identify and were probably mediated by the basal regions of the cochlea (Davis & Hirsh, 1976). Subsequent research showed that brainstem responses to low-frequency stimuli were identifiable to within 10 - 20 dB SL provided that the high-pass filter setting of the amplifier was lowered to 0.5 Hz from the usual 100 Hz (Suzuki, Hirai & Horiuchi, 1977; Suzuki & Horiuchi, 1977). After changing their high-pass filter to 40 Hz, Davis and Hirsh (1979) found the vertex-negativity following wave V to be the most prominent component of the response to low-frequency tones. They called this wave the "slow negative wave at 10 ms" or SN10. The largest brainstem responses to low-frequency tonepips are recorded using a high-pass filter setting of 10 Hz (Stapells & Picton, 1981). Using this setting one sees a broad, clear vertex-positive wave -- wave V. Higher high-pass filter settings (20-100 Hz), particularly when the rolloff slopes are greater than 12 dB/octave, result in a lower amplitude response with a prominent vertex-negative wave (Stapells & Picton, 1981). This is the SN10 of Davis and Hirsh (1979). There are now numerous reports of brainstem responses to low- and high-frequency stimuli, showing SN10 or V response thresholds of 10 - 20 dB nHL in normal subjects (Brama & Sohmer, 1977; Coats, Martin & Kidder, 1979; Davis & Hirsh, 1979; Hayes & Jerger, 1982; Klein, 1983a; Klein & Teas, 1978; Kodera, Yamane, Yamada & Suzuki, 1977; Picton, Ouellette, Hamel & Smith, 1978; Stapells & Picton, 1981; Stillman, Moushegian & Rupert, 1976; Suzuki et al., 1977; Suzuki & Horiuchi, 1977; Woods, Seitz & Jacobson, 1979).

The brainstem responses in normal-hearing subjects to the Davis tonepips are frequency-specific when the tones are presented at low to moderate intensities (50 dB nHL or less) (Klein, 1983b; Stapells & Picton, 1981). At higher intensities, however, Davis tonepips with frequencies less than 2 kHz elicit responses originating from more basal regions of the cochlea (Burkard & Hecox, 1983b; Stapells & Picton, 1981). In hearing-impaired individuals the effects are even more complex.

Where significant differences in threshold exist between different frequencies, the acoustical spread of a brief tone that is subthreshold at its nominal frequency may stimulate more sensitive cochlear regions transducing either higher or lower frequencies. This would result in an underestimation of the threshold at the nominal frequency of the tone. This is particularly true in patients with steep high-frequency hearing losses (Hayes & Jerger, 1982). A variety of masking procedures have been proposed to overcome these difficulties in obtaining frequency-specific brainstem responses.

The "Derived-Response" technique involves the recording of the ABR to clicks presented in high-passed masking noise using different filter cut-offs. Subtraction of the response to clicks in high-pass noise at one cut-off frequency from the response to clicks in high-pass noise at a higher cut-off frequency leaves a derived response to the frequencies between the two cut-off settings. Derived Responses representing full intensity series for each audiometric frequency may be obtained by recording responses to clicks at each intensity using high-pass noise masker cut-offs from 8000 to 500 Hz (Don, Eggermont & Brackmann, 1979; Picton et al., 1981). Originally proposed by Teas and his colleagues working with animals (Teas, Eldridge & Davis, 1962), this technique has been used successfully with audiologically normal humans, giving thresholds for the 1, 2, and 4 kHz center frequency (CF) bands of 10 - 20 dB (above the behavioral threshold for the unmasked stimulus) and 30 dB for the 0.5 and 8 kHz CF bands (Don & Eggermont, 1978; Eggermont & Don, 1980;

Parker & Thornton, 1978a, 1978b; Picton et al., 1981). The derived-response technique has also been used to obtain threshold information from subjects with hearing loss. Don and his coworkers found good agreement (within 15 dB) between the Derived Response threshold (corrected for normal threshold) and the pure tone behavioral threshold for the 0.5, 1, 2 and 4 kHz CF bands. The high normal thresholds for the 0.5 and 8 kHz CF bands and the high levels of noise required to mask the clicks permitted only a 40 dB range which could be tested. Don et al. (1979) did not test patients with greater losses at these frequencies.

There are several disadvantages with the derived-response technique. First, high levels of noise are required to mask the click, thus limiting the range of intensities which may be used. Second, the technique requires more on-line recording time than other techniques because a full intensity series at each frequency band must be carried out. As responses are derived off-line using subtraction, one cannot be sure during the recording whether threshold has been reached. Third, the technique requires greater off-line analysis time, and a storage and subtraction capability which many clinical averaging systems do not presently possess. These problems notwithstanding, the derived-response technique does seem to provide reasonably accurate threshold information, and may be useful for objective audiometry.

An alternative masking procedure involves the use of band-reject or "notched" noise to mask tonal stimuli (Picton et al., 1979). This technique removes the part of the response generated by those areas of the cochlea not specific to the nominal frequency of the stimulus by masking the skirts of the tonepip's frequency-spectrum (Picton et al., 1981). Using this technique, Picton and his colleagues obtained EP thresholds within 20 dB of conventional audiometric thresholds in both normal-hearing and hearing-impaired subjects, and demonstrated the technique to be particularly useful when steep high-frequency losses are present (Picton et al., 1979). Picton et al. used tonepip stimuli with 1 ms rise and fall times (no plateau), and broadband noise having a 2 octave notch centered on the nominal frequency. They showed that a noise level of 15 dB below the tonepip peak intensity (12 dB below the peak equivalent SPL) was required to ensure that the tonepip frequency splatter was sufficiently masked in hearing-impaired subjects with a steep high-frequency loss. Subsequent studies have shown that tonepips having rise-times of up to 5 ms provide better frequency-specificity without significant decrements in response amplitude (Stapells & Picton, 1981). The use of tonepips with longer rise-times than those used by Picton et al. (1979) could allow the use of lower noise intensities and narrower notches.

Picton and his coworkers briefly investigated the possibility of using unnotched broadband noise and found that this method provided about the same frequency-specificity as the notched noise technique. The drawback with the white noise method, however, was that it resulted in lower amplitude responses when noise levels greater than 30 dB below the tonepip's peak intensity were used (Picton et al., 1979). Picton et al. concluded that this technique might be worth considering if one were to use more frequency-specific tones requiring lower levels of masking noise. The advantages of this technique over the notched noise technique are its simplicity (no filter settings to change) and its lower expense (no need to purchase a multi-pole band-reject filter).

The notched noise procedure has also been used to mask clicks (Pratt & Bleich, 1982; Stapells et al., in press-b; van Zanten & Brocaar, in press). The rational for using clicks is that their rapid onset elicits a larger ABR. The initial paper by Pratt and Bleich (1982) showed large amplitude responses, the latency of which did not change with the frequency of the notch. A recent paper by van Zanten and Brocaar (in press), however, does show an appropriate increase in latency for lower frequency notches. We have found that the level of masking noise is critical for this technique, and the resulting responses demonstrate considerable inter-subject variability (Stapells et al., in press-b). The only study investigating this technique in patients reports little correlation between thresholds obtained using this procedure and those obtained using conventional audiometry (Pratt, Ben-Yitzhak, & Attias, in press).

The 40-Hz Response. The description of the auditory 40-Hz potential in 1981 by Galambos and his colleagues has awakened interest in auditory steady state potentials and their possible audiometric use (Galambos, Makeig & Talmachoff, 1981). Galambos et al. demonstrated that stimuli presented at rates of 40 - 45/s evoke a steady state potential which is two to three times the amplitude of the MLR recorded at 10/s. This 40-Hz response can be recorded in response to tonal stimuli within a few dB of threshold (Galambos et al., 1981). We have found the 40-Hz steady state potential to be a robust response which can be recorded using either conventional averaging techniques or the relatively simple and inexpensive technique of Fourier analysis (Stapells et al., in press-a). The few studies which have investigated this response have indicated that it is recordable to within 20 dB of behavioral threshold (Brown & Chambers, 1983; Brown & Shallop, 1982; Dauman, Szyfter, Charlet de Sauvage, Cazals & Portmann, 1983; Döring, 1983; Galambos et al., 1981; Klein, 1983a; Lynn, Lesner, Poelking & Daddario, 1982; Stapells et al., in press-a).

There are several problems with the 40-Hz steady state response. Little is known about the cerebral origin of the 40-Hz response, its relationship to the transient MLR, or its frequency-specificity. The effects of varying stimulus or recording parameters have not been studied. Furthermore, a number of reports have indicated that this potential decreases in amplitude by about 50% in sleep (Brown, 1982; Brown & Shallop, 1982; Dauman et al., 1983; Galambos, 1981; Klein, 1983a; Shallop & Osterhammel, 1983). Its amplitude in the awake state is sufficiently large, however, that the 50% decrease may be tolerable. Little is known of the effects of age and maturation. Although Galambos (1981) and Shallop & Osterhammel (1983) have recorded the 40-Hz response in neonates, there are instances where infants and young children show no response (Galambos, personal communication; Kileny, 1983).

Summary. The preceding discussion has outlined the many evoked potential techniques which are, or may be useful for the prediction of pure tone behavioral thresholds. The optimal stimulus, recording and subject parameters for each technique have been briefly reviewed. The number of studies which have compared the results of two or three EP techniques recorded in the same individual have demonstrated considerable variability in the thresholds obtained. These results are shown in Table 1. No clear conclusion as to the superiority of any of these methods evolves from these studies. Variations in the recording methodologies and the subjects make comparisons very difficult.

---------- Table 1 ----------

The determination of which EP technique provides the best predictions of pure tone thresholds will require that each technique be tested in the same group of subjects. As some techniques may be better for specific frequencies or types of hearing loss, stimuli of different frequencies should be used. Each technique should be used to test individuals having hearing losses with different levels of severity, audiometric configurations, and etiologies. Each technique should be evaluated using the optimal recording parameters provided that the recording times for all techniques are approximately the same.

This paper presents the results of a study to evaluate how well eight evoked potential techniques estimated the pure tone behavioral thresholds in normal-hearing and hearing-impaired subjects. A good test for EP audiometry should accurately estimate these thresholds with a high degree of consistency across different subjects. In doing so, the responses recorded using this test should be clear and obvious to different individuals. Because of the length of the recording sessions we evaluated these techniques in older children and young adults. It would not have been possible to complete the study in the infants and young children normally tested in the clinic. Furthermore, all subjects were tested while awake and reading. Later studies on the effect of subject state and age must be done, but for initial comparisons it is essential that these parameters be constant. The overall objective of this study was to provide the clinician with information necessary for choosing between different evoked potential procedures.

Method

Subjects

All subjects were paid an honorarium of $50.00: $3.00 for each of the eight EP tests and conventional audiometry, and an additional bonus of $23.00 after finishing all of the tests. All subjects (and their parents when subjects were under 18 years of age) were informed verbally and in writing of the procedures and purpose of the study, and gave their written consent to participation.

Two groups of subjects took part in this study. The "normal-hearing" group consisted of five male and five female subjects, aged between 12 and 38 years, recruited from the general population. Each subject in this group had pure tone audiometric thresholds of 15 dB HL (ANSI, 1969) or less for each of 250, 500, 1000, 2000 and 4000 Hz and 20 dB HL or less at 8000 Hz; speech reception thresholds within 10 dB of the 500, 1000, and 2000 Hz pure tone average (Bess, 1982); static compliance values within 0.3 and 1.6 cc (Jerger, Jerger, & Maudlin, 1972) and normal Type A tympanograms (Jerger, 1970). A detailed description of this group can be found in Table 2.

The "hearing-impaired" group consisted of 12 subjects, aged between 11 and 17 years of age, each having stable bilateral hearing losses of varying degree and etiology. Each of these individuals were outpatients of the Department of Audiology at the Children's Hospital of Eastern Ontario, and prior to their involvement in this study they and their parents were informed as to the nature and purpose of the study, and invited to participate. One subject dropped out of the study after two of the tests. Her data are not included in the results. Another subject from the hearing-impaired group (Subject 52) ceased participation in the study because of her sensitivity to the noise masking used in some of the EP tests. Her results will be discussed later. A detailed description of the hearing-impaired group can be found in Table 3.

---------- Tables 2 and 3 ----------

Stimuli

Stimuli were generated by a Tracor Analytic TN 3000 Clinical Averaging System, attenuated and mixed (Med Associates Inc. model ANL-918 attenuator/mixers) with noise of appropriate frequency composition and intensity (when applicable), and further attenuated before being presented to the subject's test ("ipsilateral") ear via a TDH-49 earphone mounted in a MX41/AR cushion. The noise was generated by a Med Associates noise generator (model ANL-912), filtered 96 dB/ octave for high-pass noise and 48 dB/octave for notched noise using a Krohn-Hite 3343 filter, and fed into the attenuator/mixer. Stimuli were continuously monitored on an oscilloscope prior to and after being mixed with the noise and attenuated. Broadband noise used to mask any response from the non-test ("contralateral") ear was generated by the TN 3000 system, attenuated by a Med Associates attenuator (model ANL-918), and presented to the subject using another TDH-49 earphone mounted in an MX41/AR cushion. The setup of the above system is diagrammed in Figure 1.

---------- Figure 1 ----------

Parameters such as signal rise/fall time and duration, and ipsilateral noise intensity and notch width, were chosen to provide the best compromise between frequency-specificity and response amplitude. The tonal stimuli were presented with alternating onset polarity. The clicks were presented with a rarefaction onset polarity. Stimulus presentation rates selected were those most efficient: ie. the optimal stimulus rate to obtain the best signal-to-noise ratio within a given time of averaging (Hyde & Blair, 1981; Picton et al., 1977). A detailed listing of the values of these parameters used in each EP test is found in Table 4. All testing took place in a single-walled IAC sound-attenuated chamber, the ambient acoustic levels of which were measured as 21 dB SPL using the A-weighting network (Stapells, Picton & Smith, 1982).

The stimuli and noise were calibrated daily using a Brüel and Kjaer 2209 sound level meter and NBS 9-A earphone coupler [Brüel & Kjaer type 4152 (DB 0909) with a 1-in. microphone type 4144]. Stimulus intensities are expressed in dB peak-equivalent SPL(peSPL) (Stapells et al., 1982, in press-c); noise intensities are expressed in dB SPL. Stimulus waveforms and ipsilateral noise (notched and broadband) were also amplified on a Brüel and Kjaer type 2619 preamplifier and type 2804 microphone power supply, digitized on a Tracor Northern TN 1500 signal analyzer, and their frequency spectra calculated and plotted using logarithmic axes. The frequency spectra of each of the tonal stimuli used in this study are shown in Figure 2; the spectra of the click and of the notched and broadband noise are presented in Figure 3.

---------- Table 4 and Figures 2 and 3 ----------

Normal behavioral thresholds (nHL) for each of the stimuli were obtained prior to this study by testing one ear each of 10 normal-hearing adult subjects in the IAC chamber using a Békésy tracking procedure. Only one of these subjects participated in the EP study; the other 9 participated only in this psychophysical experiment. Stimuli were routed from the TN 3000 through a Grason Stadler model 1701 audiometer, and the subject's responses recorded using the 1701's X-Y recorder. After 5 - 10 minutes of practice, tracings of three to four minutes were obtained for each stimulus. The average of ten stabilized reversals, the midpoints of which were all within 3.5 dB of each other, was taken as threshold. The mean nHLs for each stimulus presented at a rate of 10/s are presented in Table 5. The accuracy of the above technique was checked by comparing the 10/s click threshold obtained using the Békésy tracking method with that obtained in a previous study which involved a greater number of subjects and used more sophisticated psychophysical techniques (Stapells et al., 1982). The Békésy tracking procedure resulted in a slightly higher 10/s click threshold than that obtained in the earlier study -- 32.3 vs. 29.9 dB peSPL. Although small, this difference was statistically significant ($\underline{t}$ = -2.09, df = 48, $\underline{p} < 0.05$). It was probably caused by the decreased sensitivity of the Békésy procedure compared to the forced-choice threshold estimation procedures used in the earlier study. The difference was not sufficiently large, however, to be worried about for tests that were to be carried out with 10-dB accuracy. The Békésy thresholds for the tones were therefore accepted for this study. The click threshold used in the present study is that from Stapells et al. (1982).

The levels of broadband noise required to mask the various stimuli were also assessed in five normal-hearing subjects using the method of limits with 2 dB ascending and descending steps. Stimuli were presented at a rate of 10/s at 40 and 60 dB nHL; masking "threshold" was defined as the mean masker intensity which just-masked the stimulus 50% of the time. The results are given in Table 5. Assuming a minimum interaural attenuation of 40 dB (Zwislocki, 1953), the intensity of the contralateral masking noise was conservatively set at 30 dB below the level required to mask ipsilaterally. This difference between the ipsilateral stimulus and contralateral masker intensities was kept constant for all stimulus intensities.

---------- Table 5 ----------

The level of broadband noise required to mask a click was assessed in ten normal-hearing subjects. This level was used to determine the amount of noise for masking the clicks for the ABR/Clicks in Notched Noise and ABR/Derived Response tests. The masking intensity for these tests was obtained in the following manner: the masking thresholds for 60 dB nHL clicks were obtained from the 10 subjects as described above; 5 dB was added to the maximum of these thresholds and this intensity was used as the masker level for ipsilateral masking. The range of these thresholds was 77 to 83 dB SPL, thus the ipsilateral masking level for a 60 dB nHL click was 88 dB SPL.

We determined the intensity of the notched noise relative to the tone's intensity (in peSPL) in two patients (not in the EP study) with abrupt high-frequency losses (50 and 75 dB/octave). the audiograms of these subjects and the stimulus and masker levels used are presented in Table 6. The 2-1-2 tones were presented at 10 dB nHL below the patient's pure tone threshold. Their behavioral responses to these tones, mediated through the spread of energy in the tone, were then masked by notched noise. Varying the intensity of the masker using the method of limits in 2-dB steps, we determined that notched noise of 20 dB lower than the peak equivalent SPL of the tone just masked the behavioral responses of these patients. This represents an 8 dB improvement over the noise levels recommended for patients by Picton and his coworkers (1979). This is probably due to the increased frequency-specificity of the Davis 2-1-2 low-frequency tones over the much briefer tones used in the earlier study, and to the narrower notch (1 octave compared to 2 octaves).

---------- Table 6 ----------

Two normal-hearing subjects were tested to check if 100 seconds (the approximate time for two EP replications in this study) exposure to the maximum noise level of 118 dB SPL (used for ipsilateral masking of a 90 dB nHL click) would result in a Temporary Threshold Shift (TTS). Thresholds were evaluated using 5-dB steps. The results, presented in Table 7, indicate no detectable shift in threshold occurred in either subject. This agrees with the data of Ward, Glorig, and Sklar (1958), which suggest a "minimum effective time" of between 1.5 and 2.0 minutes, below which no TTS should occur. Ward et al. (1958, 1959) proposed that in normal-hearing subjects the TTS tested at 4000 Hz after exposure to broadband noise is:

$$1.06r(S - 85)(\log_{10}(T/1.7))$$

where r equals the duty cycle of the noise, S is the SPL of the noise, and T is the total duration of the exposure in minutes (Ward et al., 1958). This formula predicts that a TTS of 5 dB would occur after 142, 164, and 235 seconds of exposure to broadband noise at intensities required to mask 90, 80, and 70 dB nHL clicks respectively. Exposure times of 197, 262, and 542 seconds at these three levels would be necessary to produce a 10-dB TTS.

---------- Table 7 ----------

EP Recordings

Electroencephalographic (EEG) signals in all EP tests were recorded from the scalp using Grass gold-plated cup electrodes attached at the vertex and on the lower portion of the mastoid ipsilateral to stimulation using Beckman saline gel and collodion-impregnated gauze. An electrode placed on the contralateral mastoid served as a ground. All inter-electrode impedances were kept below 3 kOhms (measured at 25 Hz). EEG signals were amplified, filtered (12 dB/octave), and averaged using the TN 3000 system. The amplification, filter, and artifact rejection settings selected are listed in Table 4.

Experimental Procedures

Complete participation in this study included nine "tests": the eight EP tests and the conventional audiometric evaluation (pure tone, speech, and impedance audiometry). Each subject underwent the conventional audiometry (both ears) before beginning the EP tests. Following these tests, one ear was selected for testing, and this same ear was used in all subsequent tests. The ear tested in a normal subject was selected randomly; in a hearing-impaired subject the ear with the loss of interest was tested. The order of the eight EP tests was randomized, with the exception that the first EP test performed on a subject normally did not involve ipsilateral noise masking. This was done to ensure that an individual's initial introduction to EP recording procedures did not include possibly bothersome masking noise.

The order of selection of stimulus frequency within each EP test was randomized, with the exception that in the ABR/Derived Response test the responses to the unmasked click were recorded first. All waveforms were replicated. A third or fourth response was occasionally recorded when there was some uncertainty concerning the presence or absence of a response (e.g. when background noise levels were higher in one replication).

Subjects were seated in a comfortable chair, instructed to relax and asked to read something of their choice. They were not allowed to sleep, and were monitored constantly to ensure that they did not. At the end of each intensity series of a test (one series for each frequency in a test), the subject's behavioral threshold ("sensation level") for the stimulus (at the rate used in the test) was determined using the method of limits in descending and ascending 10 dB steps.

The entire battery of conventional audiometric tests and the EP tests usually lasted a total of 12 - 16 hours, which was spread out over three to five sessions (usually four), each lasting three to five hours. All tests were completed within 16 days of the first session. At the end of the final session subjects underwent pure tone audiometry of their test ear to ensure no changes in threshold had occurred.

In all EP tests except the ABR/Derived Response test, the stimulus intensity initially tested was 70 dB nHL. If a replicable response was present at this intensity, an intensity series in 10 dB decrements was performed until "no response" recordings had been collected at three consecutive intensities or until -10 dB nHL was reached. The requirement for three "no response" recordings ensured that a) a response reappearing 10 dB below where it disappeared would be recorded, and b) a "blind" rater scoring the waveforms, would have a complete set of recordings from well above to well below threshold. If either "no response" or unclear "response" waveforms were recorded at 70 dB nHL, testing was carried out at 90 or 80 dB nHL, respectively. The maximum stimulus intensity used in the ABR/Derived Response and the ABR/Clicks in Notched Noise tests was 80 dB nHL, due to the high levels of noise required to mask this stimulus. Two patients were tested at 90 dB nHL in the tests involving clicks. No further patients, however, were tested above 80 dB because of the development of a TTS in one of the patients tested at 90 dB (see Results).

The intensity series for the ABR/Derived Response test differed from the other EP tests in two ways. First, the normal-hearing subjects began at 70 dB nHL while subjects in the hearing-impaired group always began at 80 dB nHL (90 dB nHL requiring too much noise); second, recordings were made at each intensity level down to and including 0 dB nHL, regardless at which intensity no replicable responses were recorded. These changes were made because it was not until the later off-line subtraction of waveforms that one could be sure whether a response existed or not.

Data Analysis

Response Criteria. The final decision regarding the presence or absence of a response was made by combining the ratings of two individuals who were familiar with all forms of auditory EPs and their measurement. One rater (T.W.P.) had no knowledge of the behavioral thresholds of each subject or of the on-line EP threshold decisions; the other rater (D.R.S.) had full knowledge of each subject's pure tone thresholds, sensation levels, and of the on-line decision regarding threshold. Each rater separately scored each and every set of waveforms on a scale of one to four. A rating of "4" was used for replicable responses that were greater than three times the amplitude of the difference between the replications (Picton & Maru, in press) and contained a component which had the correct latency and morphology. A rating of "3" indicated a smaller response with the correct morphology and latency or, occasionally, a large response with an unusual morphology or latency. A rating of "2" indicated no replicate response at the correct latency although one might have occurred within the background noise. A rating of "1" indicated a relatively noise-free recording with no response. Thus, a score of "4" indicated a "definite response", a "3" meant a "probable response", a "2" indicated "probable non-response", and a "1" indicated "definite non-response". During recording, a response was tentatively considered "present" when a rating of "3" or "4" could be awarded. The EP waveforms were evaluated with knowledge of the intensity and frequency of the stimulus, and in order of descending intensity. Raters based their judgements on the latency/intensity and amplitude/intensity characteristics of the response in question, the waveform's morphology and replicability, and their own intuition.

The raters' scores were averaged and rounded-up to the nearest integer to obtain a combined score. Recordings with a combined score of "3" or "4" were considered as responses; a combined score of "1" or "2" indicated no response. The lowest intensity with a "3" or "4" response with no incidence of two consecutive non-response recordings above it was considered as the evoked potential threshold (EPT). If no intensity fit these criteria, the EPT was recorded as the maximum intensity tested plus 10 dB, up to a maximum of 90 dB nHL. In order to determine how well the EP test predicted a subject's pure tone threshold, their conventional pure tone threshold (CPT) for the same frequency as the EP stimulus was subtracted from the EPT, thereby providing the EP threshold minus pure tone difference (EPT-CPT), or test accuracy. If a subject had a CPT greater than 90 dB at a particular frequency, it was considered as 90 dB for the calculation of EPT-CPT differences.

The raters' scores provided two additional measures: response clarity and inter-rater reliability. Response clarity was obtained by subtracting the mean combined scores below threshold from the mean combined scores at and above threshold. The greater this difference, the easier it was to identify a response and to differentiate it from a non-response. The second measure, inter-rater reliability, was obtained by calculating the absolute difference between raters' scores for each intensity series. A reliable EP test would be one in which responses and non-responses are equally-obvious to different raters. Frequent occurrences of disagreements greater than one (eg. one rater scoring a recording as a "4" and the other rater giving a score of "2" or "1") would suggest that the test is unreliable.

Evoked Potential Measurements. Measures of latency and amplitude were obtained in the normal subjects for all recordings which had a combined rating of three or greater. These measurements were made from the average of the replicate recordings; only one component in each response was measured. These components were defined as follows:

a) Brainstem potentials (ABR): Wave V was defined as the maximum vertex-positive peak occurring between 4.5 and 16.0 ms following stimulus onset. If several peaks of equal amplitude occurred within this range, the peak preceding the largest negative shift was selected. Latency was measured to the peak of wave V; wave V amplitude was measured from this positive peak to the most prominent negative peak occurring within 6.0 ms following the wave V peak latency. If no distinct negative peak occurred, the maximum negativity within this interval was used. If the wave V peak was in the form of a plateau, the latency was taken at the center and the amplitude was measured to the maximum point on the plateau. This method of measurement for peaks in the form of plateaus was also used in the measurement of the MLR and Slow Responses.

b) Transient Middle Latency Response (MLR): Component Pa was defined as the maximum vertex-positive peak occurring between 20.0 and 50.0 ms post stimulus onset. Latency was measured to this peak, and amplitude was measured from the largest negative peak (Na) preceding Pa to the peak of Pa.

c) 40-Hz Steady State Potential: The 40-Hz Response resembles a single cycle of a 40-Hz sinusoid, hence no specific components exist. The maximum peak-to-peak deflection present in the waveform was recorded as amplitude. No latency measure was recorded.

d) Slow Response: Component N1 was defined as the most prominent negative peak occurring between 50 and 225 ms following the onset of the stimulus. Latency was measured to this peak; amplitude was measured from the N1 peak to the most prominent peak occurring within 150 ms after N1.

Statistical analyses. a) Mean latencies and amplitudes, and their standard deviations were calculated for the EP measures obtained from the normal-hearing group. Linear regressions and Pearson product-moment correlation coefficients were calculated for the normal latency-intensity and amplitude-intensity functions. Mean test accuracy (EPT - CPT), response clarity, and inter-rater reliability results were obtained from both the normal-hearing and hearing-impaired groups for each EP test at each frequency.

b) Bartlett's Test for homogeneity of variances (Bartlett, 1947) was used to determine the statistical significance of differences in the variability of the EPT-CPT measures obtained for different EP tests. This provided a measure of the "inter-subject consistency" of thresholds provided by each test. A test resulting in a wide range of EPT-CPTs demonstrates poor inter-subject consistency, whereas a range of only 5 - 15 dB across subjects shows high consistency.

c) Repeated measures analyses of variance (BMDP, 1981) were performed on the accuracy (EPT-CPT), clarity, and inter-rater reliability data from those subjects who completed all tests. Results were considered statistically significant at $p < 0.01$ using conventional degrees of freedom, and at $p < 0.05$ using the more-conservative Greenhouse-Geisser degrees of freedom adjustment (Greenhouse & Geisser, 1959). Tukey (1953) "honestly significant differences" (HSD) were calculated to perform pairwise comparisons when significant main effects and interactions were obtained. These post hoc tests were considered significant at $p < 0.05$.

The analyses of variances were performed on the test clarity and inter-rater reliability measures, even though these measures were derived from the ordinal ratings. These parametric analyses were used since the two raters used the rating-scale as an equal-interval continuum and the distributions of the ratings were approximately normal.

d) The EPT-CPT, clarity, and reliability scores were combined for each EP test to determine the test which demonstrates the best overall usefulness for EP audiometry. This was done by ranking each test's scores, and then combining these ranks so that each measure contributed equally to a final overall rank. A Friedman two-way analysis of variance (Siegel, 1956) was performed on these data, and post hoc pairwise comparisons were made using the sign test (Siegel, 1956). Results for the analysis of variance were considered significant at $p < 0.01$, while the sign test results were considered significant at $p < 0.05$.

Results

A) Normal Subjects

(i) ABR/Derived Responses. The Derived Responses from a typical subject are shown in Figure 4, and the average latency data from all ten subjects are plotted in Figure 5. At 70 dB nHL the 2000 and 4000+ Hz (4000 - 8000 Hz) Derived Responses are most similar to the response to the unmasked click. This suggests that the basal region of the cochlea provide the greatest contribution to the high-intensity unmasked response. The responses to the low-frequency (500 and 1000 Hz) bands demonstrate broad and delayed wave V waveforms. Latency of wave V increases with decreasing intensity and frequency, with values at 70 dB nHL of 5.70 (± 0.26), 6.34 (± 0.37), 7.30 (± 0.27), 9.56 (± 0.55) ms for the 4000+, 2000, 1000 and 500 Hz Derived Responses. These latencies increase linearly with decreasing intensity with slopes of 38, 40, 61, and 76 µs/dB for the 4000+, 2000, 1000 and 500 Hz recordings.

---------- Figures 4 and 5 ----------

The mean amplitude data are shown in Figure 6. There is little difference between the 500, 1000 and 2000 Hz amplitudes which decreased from 0.55 (± 0.19) µV at 70 dB to 0.25 (± 0.22) µV at 20 dB. The 4000+ Hz band responses, however, were larger and demonstrated a greater change with intensity, decreasing from 0.82 (± 0.20) µV at 70 dB to 0.28 (± 0.18) µV at 20 dB nHL. The steep slope of the 4000+ Hz amplitude-intensity function is similar to that for the unmasked click.

---------- Figure 6 ----------

(ii) ABR/Clicks in Notched Noise. The responses to Clicks in Notched Noise recorded from a better-than-average subject are presented in Figure 7. While there is some suggestion of an increase in wave V latency with decreasing centre frequency of the notch, the recordings in this condition were variable and difficult to interpret. High-frequency (4000 and 2000 Hz) responses were clearer than the low-frequency recordings, the 500 Hz notch providing responses only at the highest intensities. The mean latency of wave V at 70 dB nHL was 10.58 (± 0.77), 8.45 (± 1.43), 6.50 (± 0.46), and 6.24 (± 0.35) ms for the centre frequencies of 500, 1000, 2000, and 4000 Hz. The amplitudes were small - on average 0.16 (± 0.12), 0.14 (± 0.08), 0.21 (± 0.10) and 0.22 (± 0.07) µV at 70 dB nHL respectively.

---------- Figure 7 ----------

(iii) <u>ABR/Tones (masked and unmasked)</u>. The average wave V latencies to the 500, 1000, 2000, and 4000 Hz tones presented alone, in notched noise, and in white noise are plotted in Figures 8, 9, 10, and 11, respectively. The latency increased with decreasing tonal frequency. The latency also increased with decreasing stimulus intensity, this change being greater at the lower frequencies. Although it was clearest for the tones-alone, this frequency-dependence of the latency-intensity function remained even when the stimulus was limited to narrow regions of the basilar membrane by the masking noise. Regression lines were calculated for the effects of intensity at each frequency. The slopes of these lines for the Tones-alone results were 91, 81, 56 and 40 µs/dB at 500, 1000, 2000, and 4000 Hz. The 0 dB nHL intercepts were 14.59, 12.88, 10.35, and 8.72 ms. The slopes of the regression lines for the Tones in Notched Noise were 69, 55, 40, and 36 µs/dB at 500, 1000, 2000, and 4000 Hz. The intercepts were 15.54, 12.56, 9.88, and 8.71 ms. The slopes of the regression lines for the Tones in White Noise were 81, 58, 39 and 33 µs/dB; the intercepts were 16.70, 13.09, 10.20, and 8.82 ms. The latencies to the tones presented in white noise were slightly longer than when notched noise is used.

---------- Figures 8, 9, 10 and 11 ----------

The effects of stimulus intensity and noise masking on the amplitude of wave V are shown in Figures 12, 13, 14, and 15. The amplitude of responses to tones presented alone decreases at a rate of approximately 10-12 nV/dB from 70 dB nHL values of 0.97 (± 0.32), 0.92 (± 0.28), 0.90 (± 0.31), and 0.81 (± 0.32) µV at 500, 1000, 2000, and 4000 Hz. The addition of the masking noise markedly altered these amplitude- intensity functions: at the higher stimulus intensities, the masking noise causes a large reduction in response amplitude. The 70 dB nHL amplitudes in the notched noise condition were 0.69 (± 0.20), 0.47 (± 0.16), 0.44 (± 0.17), 0.38 (± 0.07) µV at 500, 1000, 2000, and 4000 Hz. Only small differences, however, exist between the masked and unmasked amplitudes at low intensities. The amplitude-intensity functions thus tend to be quite flat when using masking noise. The amplitudes of responses recorded with the white noise masking were slighter lower than those recorded using notched noise masking.

---------- Figures 12, 13, 14 and 15 ----------

(iv) Transient MLR (10/s). The mean latencies of the vertex-positive component Pa to 500, 1000, 2000, and 4000 Hz tonal stimuli are presented in Figure 16, while the mean amplitudes measured to the preceding negative peak (Na) are shown in Figure 17. Increasing stimulus tonal frequency resulted in a decrease of Pa latency, with 70 dB nHL latencies of 34.2 (± 4.6), 32.6 (± 4.3), 31.9 (± 5.3), and 27.8 (± 4.3) ms for the 500, 1000, 2000, and 4000 Hz tones. Decreasing the stimulus intensity results in small latency increases. The amplitudes of these responses were variable but there was a tendency for lower-frequency stimuli to elicit larger responses. The mean amplitudes at 70 dB nHL for all frequencies fell between 0.80 and 1.0 (± 0.33 to 0.50) µV. Small and inconsistent decreases in amplitude were seen with decreasing stimulus intensity.

---------- Figures 16 and 17 ----------

(v) 40-Hz Steady State Potential. Figure 18 shows a full frequency by intensity series of 40-Hz waveforms from a subject who demonstrated very clear responses. The amplitude of this sinusoidal response decreases linearly down to threshold. Low-frequency stimuli elicit larger responses than do high-frequency stimuli. The mean peak-to-peak amplitudes at each frequency and intensity are plotted in Figure 19. The mean amplitudes at 70 dB nHL were 1.00 (± 0.41), 0.87 (± 0.39), 0.81 (± 0.12), and 0.58 (± 0.15) µV for the 500, 1000, 2000, and 4000 Hz tones, decreasing linearly down to threshold with slopes of 11, 11, 11, and 6 nV/dB. The average amplitudes of the 40-Hz Responses at 10 dB nHL were 0.29 (± 0.22), 0.24 (± 0.22), 0.09 (± 0.15), and 0.07 (± 0.15) µV for the 500, 1000, 2000, and 4000 Hz tones. A mean "noise" value of 0.25 (± 0.06) µV was obtained by recording the maximum peak-to-peak amplitude present in non-response waveforms from each normal subject obtained at -10 or 0 dB nHL.

---------- Figures 18 and 19 ----------

(vi) Slow Responses. The Slow Responses from a typical normal-hearing subject are shown in Figure 20, and the average N1 latencies and amplitudes are plotted in Figures 21 and 22. There were no consistent frequency-differences in the latency of N1. The mean latency of this component at 70 dB nHL was 99.1 ms (SD = 8.2). At intensities below 40 or 50 dB nHL, latencies increased noticeably and were more variable between subjects. The amplitude of the Slow Response (N1-P2) decreases linearly with decreasing intensity, with low-frequency stimuli eliciting slightly larger responses. At 70 dB nHL, mean amplitudes for responses to the 500, 1000, 2000, and 4000 Hz tones were 9.6 (± 4.1), 10.4 (± 4.1), 8.4 (± 3.7), and 7.1 (± 3.0) µV.

---------- Figures 20, 21 and 22 ----------

B) Hearing-Impaired Subjects

(i) Subject 52 completed only the ABR/Derived Response, ABR/Tones, and Slow Response EP tests before being required to drop out of the study. This subject had a 40 - 50 dB hearing loss at the low frequencies and normal hearing at 2000 Hz and above (see Table 3). Thresholds obtained using the brainstem responses to unmasked tones were within 10 - 15 dB of her pure tone behavioral thresholds. The Slow Responses recorded from this subject were somewhat variable with EP thresholds of 10, 30, 35, and 25 dB above her 500, 1000, 2000, and 4000 Hz pure tone thresholds. The Derived Responses for 1000 and 4000+ Hz are shown in Figure 23. They demonstrate that the technique does map threshold: the high-frequency responses are recorded to within 10 dB of pure tone threshold; EP threshold at 1000 Hz was recorded as 40 dB, within 5 dB of her pure tone threshold. The 1000 Hz waveforms in Figure 23, however, also illustrate a problem inherent with the derived-response technique: when waveforms are added or subtracted, the background noise present in the waveforms add together. The result is increased waveform variability, making precise determination of EP threshold difficult. The 1000 Hz waveforms show no easily recognized response at 60 dB nHL, but the response is again visible at lower intensities.

---------- Figure 23 ----------

Another serious problem with the derived-response technique is illustrated in Figure 24. Subject 52 showed a sensitivity to the noise used to mask the click. In this subject we had used 118 dB SPL noise (broadband) to mask the 90 dB nHL clicks. She developed tinnitus and on audiometric examination showed a 30-dB temporary threshold shift (TTS) at 4000 Hz. The tinnitus lasted for 48 Hrs and her thresholds returned to pre-test levels when tested 3 days after the noise exposure. The occurrence of a TTS of this magnitude underscores the current lack of knowledge concerning the sensitivity of pathological ears to high-intensity noise. According to the Ward et al. (1958) formula, an exposure time of at least 12 minutes would have been required to produce a TTS of 30 dB in a normal ear: This subject did not participate in any further testing. Following this experience the maximum noise intensity was lowered 10 dB to 108 dB SPL, enough to mask an 80 dB nHL click. Subject 52's normal ABRs to low-intensity unmasked clicks (shown on the right of Figure 24) suggest the presence of normal sensitivity at high frequencies, and should perhaps have indicated the need for caution when using the derived-response technique.

---------- Figure 24 ----------

(ii) Subject 31 had a very steep high-frequency loss (65 dB/octave), with a 65 dB HL at 4000 Hz and normal hearing at 250 to 3000 Hz. Her brainstem responses to the masked and unmasked tones illustrate how a response may result from the spread of acoustic energy away from a tone's nominal frequency. At 4000 Hz, the brainstem responses to unmasked tones were recorded down to 10 dB nHL, underestimating her loss by 55 dB. The addition of notched noise masking improved the frequency-specificity of the response by only 10 dB (EPT-CPT = -45 dB). The response was probably mediated by her normal sensitivity at 3000 Hz, which was not masked by the notched noise. Although the waveforms were somewhat variable, the threshold of the brainstem responses to Tones in White Noise at 4000 Hz was within 5 dB of her pure tone HL, suggesting better frequency specificity with this technique when very steep losses are present. The better frequency-specificity of the longer-duration stimuli used to elicit the 40-Hz Response resulted in a 4000 Hz EPT-CPT of 5 dB. This indicated that the lower frequencies did not contribute to this response.

(iii) Subject 32 had a flat conductive loss (45 - 55 dB). In general, her EPT-CPT threshold differences were higher and response clarity measures lower than the individuals with sensorineural hearing loss. The better response clarity and threshold prediction in the sensorineural loss patients is probably related, at least in part, to the presence of amplitude recruitment in their responses (see vi below). The responses from this patient with a conductive loss are more like those of a normal-hearing individual. The effects on the ABR are illustrated in the right of Figure 25. The left of Figure 25 shows the mean latency-intensity function for the brainstem responses to unmasked clicks and 500, 1000, 2000, and 4000 Hz unmasked tones from the 10 normal-hearing subjects. The conductive loss shifted the latency-intensity curves up and to the right.

---------- Figure 25 ----------

(iv) The responses from most of the eight EP tests for Subject 33 (sloping high-frequency sensorineural hearing loss) were very clear (high ratings above threshold, low ratings below), and showed thresholds which were very close to her pure tone thresholds (most tests were within ± 15 dB). One of the exceptions to this were her transient middle latency responses, some of which are shown in Figure 26. This Figure illustrates the variability of the MLR. It is very difficult to differentiate the above-threshold responses from the recordings below threshold (particularly at 500 Hz).

---------- Figure 26 ----------

(v) The pure tone thresholds of Subject 34 (low-frequency conductive loss) were predicted fairly accurately by most EP tests. Many of her ABR waveforms, especially those in response to low-frequency stimuli, were characterized by a wave V superimposed on a large sinusoid. This was a common occurrence in many subjects (both normal and hearing-impaired). The brainstem responses from a normal-hearing subject (Subject 02) and from Subject 34 to 500 Hz unmasked tones are shown in Figure 27. They demonstrate the superimposed 40-Hz sinusoid which remains visible down to threshold. An ABR wave V which is separate from the 40-Hz Responses at high intensities, becomes indistinct below 50 - 60 dB nHL. These subjects' brainstem responses to the 4000 Hz tones, however, showed the ABR wave V as the major component down to threshold, with little evidence of the 40-Hz sinusoid.

---------- Figure 27 ----------

(vi) The phenomenon of amplitude recruitment is illustrated by the brainstem and 40-Hz waveforms of Subject 35 (45 - 75 dB flat sensorineural loss) presented in Figure 28. These responses (left and center of Figure 28) are large down to 60 dB nHL and vanish completely below this intensity. This rapid decline in amplitude over a 10 dB intensity change does not occur in a normal ear. This phenomenon aided threshold determination in many patients with sensorineural hearing loss. The Slow Responses from this subject, shown on the right of Figure 28, do not demonstrate the recruitment of amplitude so clearly: these responses are variable and show a higher threshold.

---------- Figure 28 ----------

(vii) The recordings from Subject 36 (45 - 70 dB flat sensorineural loss) showed EP thresholds which were generally within 10 dB of his pure tone thresholds. He showed similar responses to his brother Subject 35.

(viii) The steep high-frequency loss of Subject 37 resulted in a number of interesting observations. The brainstem responses to unmasked clicks, illustrated on the left of Figure 29, showed a normal wave V latency at high intensity and were recorded down to 20 dB nHL. A hearing-screening program relying upon EP threshold and/or wave V latency at 60 - 80 dB nHL would pass this subject as being normal. Her latency-intensity function (Figure 29, right), however, shows a large jump at intensities below 50 dB. The 500 and 2000 Hz Derived Responses recorded from this subject are shown in Figure 30. The broad late wave Vs of the low-intensity unmasked responses are similar to the 500 Hz Derived Responses. The jump in the unmasked latency-intensity function thus probably represents a shift in the cochlear origin of the response to a more basal region of the basilar membrane. The unmasked high-intensity response is similar to the 2000 Hz Derived Responses, suggesting that the high-frequency regions contribute to the unmasked response when the intensity reaches their abnormally high threshold.

---------- Figures 29 and 30 ----------

Figure 31 shows Subject 37's brainstem responses to 2000 Hz tones presented alone (left) and in notched noise (right). When presented alone, the spread of the tone to the more-sensitive

1000 Hz region results [illegible] an underestimation of pure tone threshold by 15 dB. When presented in notched noise threshold is raised 10 dB, such that it is now within 5 dB of pure tone threshold. The clarity of the responses to tonal stimuli (masked and unmasked) contrasts with the variability of the 2000 Hz Derived Responses from this same subject, presented in Figure 30. In this case, the variability of the Derived Responses probably was the cause of the 15 dB underestimation of her hearing loss at 2000 Hz.

---------- Figure 31 ----------

(ix) At 1000, 2000, and 4000 Hz, the various ABR tests provided recordings from Subject 38 (30 to 60 dB sloping high-frequency loss) which were clear and equally-obvious to both raters. At 500 Hz, however, thresholds were elevated an extra 5 to 25 dB over those for higher frequencies, and the raters disagreed more often.

(x) Subject 39 (20 to 50 dB sloping high-frequency loss) showed a large postauricular muscle response in most of his higher-intensity brainstem and transient MLR waveforms. This muscle response is the dominant component in the 70 and 60 dB nHL MLR waveforms shown on the left of Figure 32. At high intensities his 40-Hz Responses, presented on the right of Figure [illegible], are unusual in their morphology and may contain a steady state postauricular muscle response. These responses have peak-to-peak amplitudes which are twice that of normal subjects (over 2 µV at 70 dB), suggesting that the postauricular muscle response may contribute to the size of the 40-Hz Response in some individuals. Although not larger in amplitude, this subject's 40-Hz Responses are clearer and replicate better than his Transient MLRs, and threshold determination is much easier. This is largely due to the greater number of trials in the averages obtainable within the time limits when recording the 40-Hz Response.

---------- Figure 32 ----------

(xi) Subject 40 had a significant mid-frequency loss, with normal sensitivity at 500 Hz and below and above 4000 Hz. The 40-Hz Responses recorded from this subject plotted in Figure 33 map his audiogram (shown on the left of Figure 34), predicting within 5 dB the pure tone HLs at each frequency. His brainstem responses to unmasked clicks (Figure 34, right), however, showed no abnormalities of latency, amplitude, or threshold. Figure 35 shows the 500 and 2000 Hz brainstem responses from Subject 40 for Clicks in Notched Noise vs. Tones in Notched Noise. Both techniques predict within 5 dB of this subject's 65 dB pure tone HL at 2000 Hz. At 500 Hz, however, the Clicks in Notched Noise test overestimates threshold by 40 dB while Tones in Notched Noise predict within 10 dB of the 20 dB pure tone HL. As is obvious from this figure, the waveforms in response to the masked clicks are very small, show considerable variability, and are much more difficult to interpret than are the responses to the masked tones.

---------- Figures 33, 34 and 35 ----------

C) Test Evaluation

Four measures were used in the evaluation of each EP test: test accuracy (EPT-CPT), inter-subject consistency, response clarity, and inter-rater reliability. Raters rated each set of waveforms on a scale of one to four, and these ratings were combined to calculate the above measures. Examples of "4", "3", "2", and "1" waveforms from each of the ABR/Tonepips in notched noise, Transient MLR, and Slow Response EP tests are presented in Figure 36.

---------- Figure 36 ----------

(i) Test accuracy. The difference between EP threshold (EPT) and pure tone behavioral threshold (CPT) provides a measure of the accuracy of threshold prediction of an EP test. Figures 37, 38, 39, and 40 show the mean EPT-CPT data for each EP test from each group for 500, 1000, 2000, and 4000 Hz. The results of a repeated measures analysis of variance on this data, presented in Table 8, show significant main effects for Group (Normal vs. Hearing-Impaired), Frequency, and EP Test, as well as significant

Test X Group, Frequency X Test, and Frequency X Test X Group interactions. Post hoc Tukey HSDs were calculated for this data ($HSD_{0.05}$ = 9.3 dB), and pairwise comparisons between the results from each test at each frequency carried out.

---------- Figures 37, 38, 39, 40 and Table 8 ----------

The results from the normal-hearing subjects show that the EP tests split up into three groupings on test accuracy. At all frequencies the brainstem responses to tonal stimuli (ABR/Tones, ABR/Tones in Notched Noise, ABR/Tones in White Noise) provided the most accurate thresholds, on average within 10 - 15 dB of pure tone thresholds. At the other extreme, the ABR/Derived Response, the ABR/Clicks in Notched Noise and the Transient MLR techniques provided very poor threshold prediction at all frequencies. In between these two groupings were tests which provided accurate thresholds at some frequencies, while at the other frequencies thresholds were high. Thus, the 40-Hz steady state potential provided very good thresholds at 500 and 1000 Hz, but not at higher frequencies. The Slow Responses provided accurate thresholds only at 500 Hz.

The overall pattern of the EPT-CPT results from the hearing-impaired group was very similar to that of the normal-hearing group. The threshold prediction in the hearing-impaired group, however, was considerably better for most tests (Figures 37, 38, 39, & 40). This may be related to the decreased temporal integration in patients with sensorineural hearing loss (resulting in long duration pure tone thresholds which are closer to their brief-tone thresholds)(Chung, 1981; Stelmachowicz & Seewald, 1977), or because of the effects of recruitment (Figure 28). The ABR/Clicks in Notched Noise and Transient MLR tests resulted in poor threshold prediction at all frequencies, while the ABR/Tones in Notched Noise and the 40-Hz Steady State Potential provided very accurate thresholds at all frequencies in the hearing-impaired subjects. The inaccuracy of the 40-Hz Response at 4000 Hz in the normal-hearing subjects did not occur in the hearing-impaired subjects. The ABR/Tones provided accurate thresholds at 500, 1000, and 2000 Hz, but at 4000 Hz this technique significantly underestimated pure tone behavioral thresholds, perhaps because of spread of acoustic energy to other regions of the cochlea. The ABR/Derived Responses showed excellent threshold prediction in the hearing-impaired group at 1000, 2000, and 4000 Hz, but significantly overestimated the amount of hearing loss at 500 Hz. Similarly, the Slow Responses estimated the patients' 500 Hz thresholds very poorly, but provided good estimates for the higher frequencies.

After considering the EPT-CPT results at each frequency for each group, the data were combined to obtain the threshold prediction accuracy for each EP test for all frequencies and for all subjects. These results, shown in Figure 41, show that the brainstem responses to tones, with and without noise masking, provides the most accurate prediction of pure tone behavioral threshold, with mean overall EPT-CPT differences between 4.4 and 6.0 dB for the three tests. Next best were the 40-Hz Response and

ABR/Derived Response techniques with overall mean EPT-CPT of 9.9 and 12.6 dB respectively. The Slow Response, Transient MLR, and ABR/Clicks in Notched Noise methods resulted in the poorest overall threshold prediction (mean EPT-CPT = 15.5, 21.3 & 26.4 dB, respectively).

---------- Figure 41 ---------

(ii) Inter-subject consistency. Bartlett's Test for homogeneity of variances was used to determine whether threshold predictions (EPT-CPT) were significantly more variable between subjects for some EP tests compared to others. The Bartlett statistic (B) was first calculated for the data from both groups and all frequencies, resulting in a statistically-significant B of 111.7 (F = 15.88, df = 7, 399426, $p<0.00001$). Following this, the Bartlett statistic was calculated for each possible pairwise comparison between the EPT-CPT variances of EP tests, using a chi square (df = 1) for significance testing. These pairwise comparisons are presented in the matrix in Table 9, and were considered significant at $p<0.05$. The results of the Bartlett Tests show that the ABR/Derived Response, the Transient MLR, and the ABR/Clicks in Notched Noise tests show the highest inter-subject variability. The threshold predictions provided by the other EP tests, on the other hand, are significantly less variable. This is particularly true of the ABR/Tones in White Noise technique, which provided the least-variable threshold predictions.

---------- Table 9 ----------

(iii) Response clarity. A measure of how distinct above-threshold responses are from below-threshold waveforms -- response clarity -- was obtained by calculating the mean combined rating above and at threshold and subtracting from it the mean combined rating below threshold. The higher the result, the greater the clarity. This calculation was made within each intensity series for each frequency, EP test, and group. No significant main effects of group ($F = 2.04$, df = 1, 18, $p=0.1699$) or frequency ($F = 0.74$, df = 3, 54, $p=0.5332$) were seen; significant differences, however, existed between the response clarities obtained using different EP tests ($F = 24.99$, df = 7, 126, $p<0.0001$ (conventional and Greenhouse-Geisser)). The response clarities were collapsed across groups and frequencies, and are shown in Figure 42. Three EP test procedures resulted in overall mean response clarities of 2.0 or less:Transient MLR, ABR/Derived Responses, ABR/Clicks in Notched Noise. These were significantly worse than the other five EP tests which resulted in overall mean response clarities of 2.4 to 2.5 (Tukey $HSD_{0.05} = 0.37$). The clarity results are reflected in the number of times extra replications were required during a test. The ABR/Clicks in Notched Noise and the MLR tests required extra replications at approximately 16 and 9 percent of the intensities tested. This contrasts with only 2 percent for the ABR/Tones test.

---------- Figure 42 ----------

(iv) Inter-rater reliability. This measure was calculated by obtaining the absolute difference ('disagreement') between the ratings provided by the two raters. No significant main effects of group ($F = 0.04$, df = 1, 18, $p=0.8344$) or frequency ($F = 1.09$, df = 3, 54, $p=0.2031$) occurred, but significant differences were seen with different EP tests ($F = 7.27$, df = 7, 126, $p<0.0001$ (conventional and Greenhouse-Geisser)). Figure 43 shows the mean overall inter-rater reliability (collapsed across groups and frequencies) for each EP test. The lower the disagreement, the better the reliability. The three brainstem procedures using tones (ABR/Tones, ABR/Tones in Notched Noise, ABR/Tones in White Noise) resulted in the best inter-rater reliability, with mean overall disagreement of 0.27, 0.32, and 0.31 respectively. The Transient MLR and the ABR/Clicks in Notched Noise tests showed the highest levels of inter-rater disagreement -- both 0.47 -- which is significantly higher than that for the ABR/Tones alone test (Tukey $HSD_{0.05} = 0.19$).

---------- Figure 43 ---------

(v) Combined results. The EPT-CPT, clarity, and inter-rater reliability data from each EP test were ranked and these ranks combined to determine which test demonstrates the best overall performance on all three of these measures. The Friedman two-way analysis of variance indicated that significant differences exist between the combined ranks of the EP tests ($\chi_r^2 = 75.76$, df = 7, $p < 0.0001$). As with the parametric tests performed on the individual measures, *post hoc* pairwise comparisons using the sign test (shown in Table 10) show that the EP tests divide into three categories of usefulness for audiometry. The brainstem responses to tones (masked and unmasked) are the most-suited for EP audiometry. The 40-Hz Responses and the Slow Responses comprise a second category. They show poorer performance than most of the tests in the first category, but considerably better performance than those tests in the third category. The 40-Hz Responses were deemed to be in this middle category because their combined results were not significant from those for the Slow Responses, and their rank sum represented a large increase over the scores for the tests in the first category (Table 10). The third category is comprised of the ABR/Derived Response, Transient MLR, and ABR/Clicks in Notched Noise tests.

--------- Table 10 ---------

Discussion

A) Normative Data

Our results from the normal-hearing group confirm previously reported findings with the auditory evoked potentials (see reviews by Davis, 1976; Gibson, 1978; Picton et al., 1977, 1979, 1981; Starr & Don, in press). They will be considered with respect to three general principles: the effects of stimulus intensity; the effects of stimulus frequency; and the effects of stimulus masking.

Effects of stimulus intensity. As stimulus intensity decreases, the latencies of the auditory EP components increase and their amplitudes decrease. The mean ABR wave V latency to a 70 dB nHL 500 Hz tone in notched noise was 10.51 ms, which increased to 13.40 ms at 30 dB nHL. The MLR Pa, however, only increased about 2 ms (34.18 to 36.07) over the same intensity range. This is slightly less than the latency changes reported by others (Picton et al., 1977; Thornton, Mendel, and Anderson, 1977). The Slow Responses (N1) increased from 95.9 to 120.3 ms. As intensity decreases the rise time of post-synaptic potentials becomes longer. The increasing intensity-related latency changes for the slower components probably reflect the cumulative effect of more synapses.

Amplitudes of auditory EPs generally decline with decreasing stimulus intensity, with this effect being most evident for the later components. Amplitude of N1 in response to a 70 dB nHL 500 Hz tone was 9.6 µV, which decreased to 4.7 µV at 30 dB. The brainstem response (500 Hz tone in notched noise) changed from 0.69 µV to 0.53 µV over the same range. Evoked potential amplitudes may saturate at high intensities, especially for high-frequency stimuli (Davis, 1976; Picton et al., 1977, 1981). Our results, however, do not show this saturation. This is probably because we did not use high intensity stimuli (80 or 90 dB) in the normal subjects.

Effects of stimulus frequency. Decreasing the tonal frequency of a stimulus results in longer ABR (V) and MLR (Pa) latencies. The increased latency reflects the time taken by the travelling wave along the basilar membrane to reach the apical regions of the cochlea. The 3 - 5 ms delay between high (4 - 8 kHz) frequency to low (500 Hz) frequency regions is accurately seen in the AP of the electrocochleogram and wave V of the brainstem response when the Derived Response technique is used. At 70 dB nHL the latency delay from 4000 to 500 Hz was 3.86 ms for the Derived Responses, 4.18 ms for the responses to tones in notched noise, 4.32 ms for the responses to tones in white noise, and 6.34 ms for the MLR. The Slow Response (N1) does not demonstrate this frequency effect on latency.

The amplitude of auditory EP components tend to be larger with low-frequency stimuli. One possible explanation is that the larger amplitude of the responses to the low-frequency stimuli reflect an increase in the area of basilar membrane activation occurring with decreasing tonal frequency (Galambos et al., 1981). The effects of tonal frequency on the amplitude of the ABR are confounded, however, by the poorer synchrony of responses from apical regions of the cochlea. The increase in the area of the basilar membrane stimulated results in increased variability of the onset of neuronal responses. This jitter may result in broader responses of lower amplitude (Stapells & Picton, 1981; Starr & Don, in press).

<u>Effects of stimulus masking</u>. The effects of masking on the latency and amplitude of the brainstem response are complex. The addition of notched or white noise to moderate- or high-intensity

tones caused an increase in the latency and a decrease in the amplitude of wave V compared with the unmasked response.

The latency shift which occurs with the addition of masking noise is greater for low-frequency tones, and decreases with decreasing stimulus intensity. Brief tones contain acoustic energy at frequencies higher and lower than their nominal frequency. The effects of the masker on the responses to low-frequency stimuli are probably the result of the masker removing the part of the response originating from the higher frequency region. The latency changes seen with the 500 Hz tone are thus due to the masker limiting the response to apical regions of the cochlea, and reflect the increased travelling-wave delay (Burkard & Hecox, 1983; Picton et al., 1979; Stapells & Picton, 1981). At lower intensities the masker has less effect because the skirts of the tone's frequency spectrum are becoming sub-threshold (Picton et al., 1981). High-frequency stimuli show little change in latency with the addition of masking noise because the response cannot shift far to an earlier and more synchronizable region of the cochlea (Stapells & Picton, 1981). The small shifts which are seen at the high frequencies are probably due to the effects of masking at the nominal frequency of the tone (Burkard & Hecox, 1983; Picton et al., 1979), the effects of which are most pronounced at high-frequencies (Burkard & Hecox, 1983). This may also account for a small part (less than 1 ms) of the latency-shift seen with the low-frequency stimuli. Similarly, the longer latencies produced by the white compared to notched masking noise are the result of increased masking at the nominal frequency.

The flattening of the amplitude-intensity relationship which occurs at all frequencies when masking noise is added is caused primarily by the removal of underlying components that derive from other frequency regions of the cochlea. Some of the amplitude changes are also attributable to a direct masking effect, both from the low-frequency edge of the notched noise and from energy present at the nominal frequency (Burkard & Hecox, 1983; Picton et al., 1979, 1981). The decreasing effect of the masker on the amplitudes which occurs with decreasing intensity occurs because the skirts of the tone become sub-threshold. The lower amplitudes of the ABR to tones in white noise are the result of the additional masking which occurs without the notch.

The changes in the amplitude and latency of the ABR to low-frequency stimuli which occur when masked indicate that these responses are not frequency-specific when recorded at moderate to high intensities (Burkard & Hecox, 1983; Klein, 1983b; Picton et al., 1979, 1981; Stapells & Picton, 1981). These results demonstrate the need for the use of noise masking when recording responses to these stimuli.

B) Audiometric Usefulness

This section will discuss the audiometric usefulness of the various EP techniques with particular attention to hearing-impaired subjects. Our results indicate that of the eight EP tests, the auditory brainstem responses to tonal stimuli (masked and unmasked) best fit the requirements for a good test for frequency-specific EP audiometry. These requirements are: (a) accurate prediction of pure tone behavioral threshold; (b) consistency of threshold prediction across different subjects; (c) ease of distinguishing above-threshold responses from below-threshold responses; and (d) inter-rater reliability.

Tests with Poor Scores. Three EP tests gave poor scores consistently for the four measures used for test evaluation. The results of this study suggest the ABR/Derived Response, ABR/Clicks in Notched Noise, and Transient MLR techniques are not useful for frequency-specific EP audiometry.

(i) ABR/Derived Responses. The derived brainstem responses demonstrated poor response clarity, a major problem if this technique is to be used for audiometry. The variability evident in some of the Derived Responses presented in Figures 23 and 37 is due primarily to the increase of background noise which occurs when waveforms are subtracted. The subtraction of one waveform from another increases noise levels by a factor of approximately 1.4 ($\sqrt{2}$) (Picton, Linden, Hamel, & Maru, 1983; Picton, Stapells, & Campbell, 1981). The resulting problem in recognizing the responses makes determination of threshold very difficult. The poor performance of this technique at 500 Hz might have been improved by using a longer-duration click containing more low-frequency acoustic energy. The derived-response technique has proven to be very accurate in electrocochleography (Eggermont, Spoor, & Odenthal, 1976;

Elberling, 1974), and theoretically it provides the best frequency-specificity of any of the EP tests evaluated in the present study. Increasing the number of trials in the averages would probably have improved the overall performance of the ABR/Derived Response technique. This would, however, decrease its usefulness since it already requires more time than the other tests because of the off-line analysis,.

A second problem with the derived-response technique is the high intensity of noise required to mask the click. High acoustic noise levels tend to make the subject tense, and this increases the electrical noise in the recordings. Most importantly, however, the high intensity masking noise can cause a temporary threshold shift. This is difficult to predict since little is known of the noise-sensitivity of pathological cochleas.

(ii) ABR/Clicks in Notched Noise. The ABR/Clicks in Notched Noise test provided the worst results of all measures. The waveforms recorded using this technique were very noisy and variable. As with the Derived-response technique, high levels of masking noise are required to mask the click. This entails the problems of muscle tension and temporary threshold shift. In addition to these serious practical problems, the cochlear mechanisms of the brainstem response to Clicks in Notched Noise are not understood. The alterations in wave V latency which would be predicted for changes in notch center frequency are not always apparent (Pratt & Bleich, 1982; Stapells et al., in press-b). The intensity of the masker relative to the click is critical, with different peaks occurring at different levels (Stapells et al., in press-b). Our results indicate that the ABR/Clicks in Notched Noise technique is not useful for EP audiometry, a conclusion supported by Pratt and his colleagues (Pratt et al., in press).

(iii) Transient Middle Latency Response. The Transient MLRs provided results which were almost as poor as the ABR/Clicks in Notched Noise technique. Noisy, variable waveforms are again the cause of the problems. The contribution of reflex and on-going muscle activity to the MLR (Bickford, 1972; Picton, Hillyard, Krausz, & Galambos, 1974) is probably the cause of the variability. The presence of a large reflex response can demonstrate that the cochlea and brainstem have responded to the sound. Problems occur, however, when a small reflex response overlaps with the neurogenic response producing a distorted and uninterpretable waveform (Picton & Fitzgerald, 1983; Picton et al., 1977). The audiometric usefulness of MLRs is probably increased during light sleep, when muscle activity decreases (Picton & Smith, 1978); indeed, this has been shown by Mendel et al. (1975), who reported lower MLR thresholds during light sleep than during wakefulness.

The MLR may have provided better results if different amplifier filter settings had been used. Suzuki and his colleagues have reported that when responses are digitally filtered using a high pass setting of 30 Hz for adults and 20 Hz for children, much of the MLRs' variability disappears (Suzuki, Hirabayashi, & Kobayashi, 1983; Suzuki, Kobayashi, & Hirabayashi, 1983). These results would probably not occur with analog filtering because the phase-distortion of the waveforms would make the interpretation of the responses more difficult.

Tests with Intermediate Scores. Two EP tests (Slow Responses and the 40-Hz Response) fell into a middle category in the overall evaluation of their usefulness for audiometry. This was due either to their intermediate performance on all measures, or to poor performance at some frequencies. These tests, however, were significantly better than the tests discussed in the previous section.

(i) Slow Response. The Slow Responses showed intermediate scores at all frequencies for accuracy, inter-subject consistency, and inter-rater reliability. The exception to this was their poor accuracy in predicting 4000 Hz thresholds, due probably to the lower amplitude of these responses at this frequency (see Figure 22)(Picton et al., 1977). In general, the Slow Responses demonstrated good response clarity. During sleep these responses are larger in amplitude, but show greater response variability (Campbell & Bartoli, 1983; Davis, 1976; Mendel et al., 1975; Picton et al., 1977). These responses would therefore not be any better when testing sleeping subjects. The Slow Responses, however, do appear to be useful in testing older children and adults with functional hearing loss (McCandless & Lentz, 1968; Picton & Smith, 1978; Picton et al., 1977; Squires & Hecox, 1983).

(ii) 40-Hz Steady State Response. The 40-Hz Response fell into the middle category because of poor scores at 2000 and 4000 Hz, particularly for the EPT-CPT accuracy measure. The 40-Hz Response, however, provided excellent scores at the low frequencies, and it may be possible to use this test at low frequencies with another (one of the auditory brainstem response techniques) for testing high frequencies. This could be done by presenting the tones which are used to elicit the brainstem responses at a rate of 40/s, and using a filter bandpass which will allow the recording of both responses (such as 10 - 3000 Hz). We used a 39/s stimulus repetition rate when recording the brainstem responses as this was close to the fastest rate allowed using a sweep of 20 ms, and previous studies had demonstrated that a rate around 40/s was optimal for recording large brainstem responses (Hyde & Blair, 1981; Picton et al., 1979). Our ABR protocol thus fortuitously combined the 40-Hz Response with the brainstem response. A large 40-Hz sinusoid is seen in many of the ABR recordings (Figure 27). The 40-Hz sinusoid is also clearly evident in most of the tracings presented in the initial notched noise study by Picton and his coworkers (1979). The major difference in this study between the ABR and 40-Hz protocols was the use of tones having longer rise-time and duration for the latter technique. The low amplitudes and high thresholds we found for the 40-Hz Responses at 4000 Hz are probably due to the use of stimuli with longer rise-times -- 0.5 ms vs 5.0 ms (Stapells & Picton, 1981). This would have caused the comcomitant 4000 Hz ABR to be smaller in amplitude. It was not possible to filter out this 40-Hz activity to separate the two responses because at lower tonal frequencies they share similar frequency spectra (Boston, 1981; Elberling, 1979). A slower repetition rate such as 10/s would have been required to separate the ABR from the 40-Hz Response.

While the 40-Hz test scored considerably better than the Transient MLR, it's results may have been further improved by employing a different filter bandpass (for the same reasons presented above for the MLR). The usefulness for audiometry of the 40-Hz technique may be substantially improved by using Fourier analysis, which can be considered as the "ultimate" bandpass filter. We have found that Fourier analysis and conventional signal averaging provide similar results; Fourier analysis, however, may be used in conjunction with techniques such as the "zoom" technique to speed up the recording, analysis and output of data (Stapells et al., in press-a). In the present study we evaluated only the amplitude of the 40-Hz Response. Recent evidence, however, suggests that phase is a more-sensitive and less-variable measure for response detection near threshold (Makeig & Galambos, 1983).

<u>Tests with Best Scores: ABR/Tones (masked and unmasked)</u>. The three brainstem response techniques using tonal stimuli proved to the best EP tests for audiometry. On average, detectable responses were recordable using low- and high-frequency tones to within 4 - 6 dB of pure tone behavioral thresholds. Test accuracy, inter-subject consistency, response clarity, and inter-rater reliability measures were consistently better for the

ABR/Tones-alone, ABR/Tones in Notched Noise, and ABR/Tones in White Noise tests than for any of the other EP tests. The clarity of the brainstem responses to tonal stimuli was not significantly changed when notched masking noise was introduced. The masking noise intensities required to mask the acoustic spread of the tones are at least 20 dB lower than those required to mask click stimuli. The masked tone tests therefore are much less likely to cause temporary threshold shifts.

Greater differences between the thresholds for the masked and unmasked tone ABRs were predicted. Unmasked techniques would be accurate for losses which are flat or sloping in configuration. The need for masking increases, however, with the steepness of a hearing-loss present (Picton, 1978; Picton et al., 1979). The results from the two patients in the present study having steep high-frequency hearing loss show a 10-dB improvement in threshold prediction when notched noise masking is used. The earlier study of Picton et al. (1979) demonstrated improvements as great as 30 dB. The results from subject 31 illustrate the effects of acoustic spread and its masking. Her 4000 Hz threshold was underestimated by 55 dB when masking is not used. Notched noise did not mask adequately the 3000 Hz region, hence threshold prediction was improved only 10 dB. The responses to Tones in Notched Noise therefore represent activity over areas of the cochlea representing approximately one octave (Picton et al., 1979). When the tone was masked using white noise, however, frequency-specificity was improved such that EP threshold predicted within 5 dB her pure tone behavioral threshold. The better performance of the white noise over notched noise masking in this case was, however, unusual. In most cases the white noise technique provided less-clear responses because they were lower in amplitude than when notched noise is employed. An unequivocal demonstration of the relative efficiency of notched or white noise masking will require the evaluation of these techniques in additional subjects with steep hearing loss.

C) General Comments

In carrying out the present study we did not determine which EP test might be the best procedure to obtain accurate thresholds under optimal recording conditions. It is possible that some of the tests would have fared better in the final comparison if recording had been carried out for a greater number of averages. However, this would result in recording times longer than would be acceptable in the clinic. Furthermore, allowing a greater number of averages may not have drastically altered this study's conclusions since the two tests with the poorest results (Transient MLR and ABR/Clicks in Notched Noise) were also the tests in which the greatest number of extra replications were obtained.

An EP test which results in high thresholds in normal-hearing subjects can still accurately predict thresholds in hearing-impaired subjects if these thresholds are consistent. This may be done by subtracting a constant "correction factor" (such as the normal threshold) from the patient's threshold (Don et al., 1979). We were unable to do this in the present study because the tests which provided high EPT-CPT scores also demonstrated considerable variability across subjects. When the variability of the threshold estimate exceeds the correction factor, the use of such a factor gives little improvement.

Ultimately evoked potential audiometry will use automatic and objective decisions regarding the presence and quality of a response (Don, Elberling, & Waring, 1983; Elberling & Don, 1983; Picton, Linden, Hamel, & Maru, 1983). In contrast with the present method which used a fixed number of trials for each average, an automatic technique would stop the averaging process when a response reaches some criterion for detection. Thus, on occasions when recordings are particularly noisy, averaging would continue until the criterion is finally attained or the trial aborted. When the recordings are clear and noise-free, criterion would be reached very quickly and the test completed in shorter time. This technique would rule out the present problem which occurs when interpreting the results from a patient whose EPs recorded one day are noisier than those recorded on another day.

Click-evoked brainstem potentials are the most common technique presently used for evoked potential audiometry. As broadband stimuli, clicks can provide a rough estimation of auditory sensitivity. Thus, if the ABR/Click threshold and latency-intensity function are normal then overall auditory sensitivity may be such that the individual is able to function normally. While probably true for the majority of hearing losses, individual cases such as subject 40 (significant mid-frequency loss) indicate that this protocol may miss individuals with significant hearing handicap. Auditory function and sensitivity demonstrated using clicks must therefore be interpreted with the limitations of the technique kept in mind.

Click-evoked brainstem potentials are used to generate the synchronized response containing waves I, III and V used in neurological evaluation. Tonal stimuli do not elicit a well synchronized response, and difficulties can arise when hearing loss is present. Click-evoked brainstem potentials are thus useful as an initial tool for screening both neurological function and hearing. When a hearing loss is indicated by this technique, however, a more-detailed examination to obtain frequency-specific thresholds is required. This examination is required in order to determine if any residual hearing is present (especially low frequency) and to obtain the threshold information needed for the fitting of a hearing aid.

D) Recommendations

The results of the present study can be summed-up by the following recommendations for evoked potential audiometry:

(i) A general auditory evaluation and screening for hearing loss is best carried-out by recording the ABR in response to unmasked clicks. This test can be carried-out very quickly, provides a rough overall assessment of auditory sensitivity, and provides information concerning the maximum stimulus and masker intensities needed in frequency-specific techniques. The relative insensitivity of wave V to high stimulus presentation rates (Picton et al., 1981) allows one to use rates from 50 to 80/s, thus speeding-up the recording-time and a full intensity series can be obtained relatively quickly. In addition to the threshold, a response to high-intensity clicks (60 - 90 dB nHL) presented at rates between 10 to 20/s may be obtained to assess neurological function.

(ii) Frequency-specific information should be obtained in those individuals demonstrating elevated ABR/Click thresholds and/or abnormal latency-intensity functions, or who, for some other reason, are suspected of having impaired auditory function. This information is required for the fitting of hearing aids and subsequent management of the patient. The method of choice for obtaining the frequency-specific information is the ABR/Tones in Notched Noise technique. Presenting the Davis 2-1-2 tones in the presence of notched noise at an intensity 20 dB below the peak equivalent intensity of the tone ensures fairly good frequency-specificity at 500, 1000, 2000, and 4000 Hz. The use of a 40/s presentation rate combines the ABR with 40-Hz Response, thus providing good response identification and low thresholds at all stimulus frequencies. These combined responses are perhaps best recorded using a wide amplifier bandpass of 10 - 3000 Hz.

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Table 1

Differences Between Thresholds Obtained Using Different Evoked Potential Techniques.

	Brainstem Responses	Middle Latency Response	Slow Responses	40-Hz Response
Electro-cochleography	+7.5[a]	+6.4[a]	+34.8[a] +17.8[g]	
Brainstem Responses		-1.2[a] +1.5[c] +2.4[e] -15[b]	+27.3[a]	-20[b] +5[d]
Middle Latency Response			+28.5[a] +8.5[f]	-5[f]

Note. The number in each column represents the dB difference between the average threshold using the technique described in the title of the column and the average threshold obtained using the technique described in the title of the row. A negative sign indicates the column technique provides a lower threshold. Brainstem responses include SN10 data.

[a] Kohzu, 1980
[b] Brown & Chambers, 1983
[c] Özdamar & Kraus, 1983
[d] Shallop & Osterhammel, 1983
[e] Musiek & Geurkink, 1981
[f] Mendel, Hosick, Windman, Davis, Hirsh, & Dinges, 1975
[g] Ino, 1976 (4000 Hz, Hearing-Impaired)

Table 2
Normal Hearing Group

Subject	Sex	Age	Ear	Pure Tone Audiogram in dB HL (ANSI,1969) 250	500	1000	2000	4000	8000	SRT[a]	Tymp[b] Type	Static Comp(cc)
01	M	24	R	0	5	5	0	5	5	10	A	0.6
02	M	20	R	0	0	0	0	-5	-5	-5	A	0.9
03	M	12	L	10	10	0	0	5	20	10	A	0.8
04	M	38	L	10	10	15	15	10	10	10	A	0.6
05	M	15	R	0	5	0	-10	0	10	5	A	0.8
11	F	29	L	15	10	15	10	10	5	10	A	0.4
12	F	23	L	10	10	10	10	10	5	5	A	0.8
13	F	23	L	15	5	5	10	10	10	-5	A	0.4
14	F	22	R	15	5	0	10	15	15	0	A	0.7
15	F	24	R	0	0	0	-5	5	5	0	A	0.9
MEAN		23		7.5	6.0	5.0	4.0	6.5	8.0	4.0		0.7
s.d.		7.1		6.8	3.9	6.2	8.1	5.8	6.7	6.2		0.2

[a] SRT = Speech Reception Threshold

[b] Tympanogram classification from Jerger, 1970

Table 3
Hearing-Impaired Group

Subject	Sex	Age	Ear	Pure Tone Audiogram in dB HL (ANSI,1969) 250	500	1000	2000	4000	8000	SRT[a]	Tymp[b] Type	Static Comp(cc)	Etiology[c]
31	F	12	L	10	15	15	0	65	65	10	A	0.5	SN
32	F	15	R	55	50	45	45	45	50	50	B	0.1	COND
33	F	13	R	15	35	60	60	55	35	40	A	1.0	SN
34	F	13	R	75	65	55	40	35	40	50	B	0.1	COND
35	M	13	R	45	60	70	65	55	70	55	A	0.7	SN
36	M	17	R	45	50	60	65	60	35	60	A	0.7	SN
37	F	11	R	10	10	20	55	65	75	20	A	0.9	SN
38	F	11	L	30	50	65	65	65	90	50	A	0.7	SN
39	M	14	L	20	25	30	40	50	45	25	A	0.6	SN
40	M	13	L	20	20	65	65	55	25	45	A	0.9	SN
52	F	17	L	50	40	35	5	5	15	20	A	0.7	SN
MEAN s.d.		13.5 2.1											

[a] SRT = Speech Reception Threshold
[b] Tympanogram classification from Jerger, 1970
[c] Etiology: SN = Sensorineural loss; COND = Conductive loss

Table 4
Stimulus, Ipsislateral Noise, and EEG Recording Parameters

Condition	Frequency (Hz)	Stimuli Rise/Fall (ms)	Plateau (ms)	Rate (/s)	Ipsilateral Noise Masker	Filters (Hz)	EEG/Averaging Sweep (ms)	# of Aver	Artifact (uV)
ABR/Derived responses	click	0	0.1	39	Noise high-pass filtered at 4, 2, 1, and 0.5 kHz	25-3000	20	2000	±20
ABR/Clicks in notched noise	click	0	0.1	39	Band-reject noise (one-octave width notch centered on 0.5, 1.0, 2.0 & 4.0 kHz)	25-3000	20	2000	±20
ABR/Tones	500 1000 2000 4000	4.0 2.0 1.0 0.5	2.0 1.0 0.5 0.25	39 39 39 39	none	25-3000	20	2000	±20
ABR/Tones in notched noise	—	same as ABR/Tones		—	Band-reject noise, with one octave-wide notch centered on nominal frequency of tone. Broadband intensity 20 dB below tone peSPL	25-3000	20	2000	±20
ABR/Tones in white noise	—	same as ABR/Tones		—	Broadband noise (no notch). Intensity 20 dB below tone peSPL.	25-3000	20	2000	±20
Transient MLR	500 1000 2000 4000	5 5 5 5	5 5 5 5	9.6 9.6 9.6 9.6	none	10-1500	50	500	±50
40-Hz Steady state potential	-- same as Transient MLR --			39	none	10-1500	25	2000	±50
Slow responses	500 1000 2000 4000	20 20 20 20	20 20 20 20	.99 .99 .99 .99	none	1-30	500	50	±100

Table 5
Normal Behavioral Thresholds[a]

Frequency (Hz)	Rise/Fall (ms)	Plateau (ms)	Threshold (dB peSPL)	Masking Threshold (dB SPL)
500	4	2	24.6	26.9
	5	5	23.6	31.6
	20	20	17.3	28.8
1000	2	1	23.2	21.1
	5	5	17.8	24.0
	20	20	13.3	26.6
2000	1	0.5	26.1	20.8
	5	5	18.4	25.4
	20	20	15.1	28.6
4000	0.5	0.25	29.0	22.6
	5	5	19.2	24.8
	20	20	14.8	25.2
Click	0	0.1	29.9[b]	19.6

[a] Stimulus presentation rate: 10/s
Number of subjects. Stimuli: 10 (Click: 40) Noise: 5 (Click: 10)

[b] Click threshold from Stapells, Picton, and Smith (1982)

Table 6
Notched Noise Masking Level Study

Subject	dB HL (ANSI, 1969) 250	500	1000	2000	4000	8000
JS	5	5	55	85	85	-
CY	0	0	0	75	80	75

Subject	Frequency (Hz)	Intensity (dB nHL/dB pe SPL)	Notch Noise Masker Threshold (dB SPL)
JS	1000	45/68	53
	2000	75/101	81
CY	2000	65/91	71
	4000	70/99	74

Table 7
Broadband Noise Exposure Study[a]

Subject	Freq(Hz)	Pre-Exposure HL	Post-Exposure HL 2 min	Post-Exposure HL 4 min	Post-Exposure HL 6 min
DRS	2000	5	0	5	5
	4000	0	0	5	5
	6000	10	10	5	10
LMM	2000	0	–5	–5	-
	4000	5	5	5	-
	6000	10	15	10	-

[a] Duration of noise exposure: 100 seconds
Noise intensity: 118 dB SPL
Threshold obtained using Method of Limits using 5 dB steps.

Table 8
Analysis of Variance: Test Accuracy (EPT-CPT)

Source	df	Mean Square	F	Tail Probability	Greenhouse-Geisser Probability
Mean	1	103530.625	99.09	0.0000	-
Group	1	29430.625	28.17	0.0000	-
Error	18	1044.861			
Frequency	3	1846.875	6.84	0.0005	0.0011
F x G	3	568.542	2.10	0.1103	0.1205
Error	54	270.093			
Test	7	5010.625	22.71	0.0000	0.0000
T x G	7	1018.482	4.62	0.0001	0.0022
Error	126	220.655			
F x T	21	498.065	5.26	0.0000	0.0000
F x T x G	21	189.018	2.00	0.0060	0.0447
Error	378	94.616			

Table 9

Inter-Subject Consistency of Overall EPT-CPT

	ABR/Tones in white noise	ABR/Tones in notched noise	40-Hz response	ABR/Tones alone	Slow response	ABR/Derived response	MLR (10/s)	ABR/Clicks in notched noise
Variability (dB)	10.1	10.9	11.6	13.0	13.5	17.2	18.7	24.7
Bartlett Statistic Matrix								
ABR/Tones in white noise		0.55	1.59	5.18*	6.72**	21.75**	28.37**	56.14**
ABR/Tones in notched noise			0.27	2.37	3.46	15.69**	21.50**	46.99**
40-Hz Response				1.05	1.81	11.99**	17.20**	40.96**
ABR/Tones alone					0.10	6.80**	10.02**	30.03**
Slow Response						4.62*	8.14**	26.89**
ABR/Derived Response							0.51	9.87**
MLR (10/s)								5.96*

Note. "Variability" = Standard Deviation of overall EPT-CPT.
Overall Bartlett Statistic (_B_) = 111.66 (_F_ = 15.88, df = 7,399426, _p_ <0.00001).
Significance of _B_ from pairwise comparisons tested using chi square with 1 df.

* _p_ <0.05
** _p_ <0.01

Table 10

Combined Overall Test Evaluation (Ranks)

	ABR/Tones alone	ABR/Tones in notched noise	ABR/Tones in white noise	40-Hz response	Slow response	ABR/Derived response	MLR (10/s)	ABR/Clicks in notched noise
Rank sum	54.0	56.5	58.5	67.5	91.5	122.0	128.0	142.0
Sign Test: Tail Probability								
ABR/Tones alone	1.0000	0.8238	0.8238	0.8238	0.0118	0.0000	0.0000	0.0000
ABR/Tones in notched noise		1.0000	0.8238	0.2632	0.0636	0.0004	0.0000	0.0000
ABR/Tones in white noise			1.0000	0.6476	0.0414	0.0000	0.0004	0.0000
40-Hz Response				1.0000	0.1153	0.0118	0.0004	0.0000
Slow Response					1.0000	0.2632	0.0026	0.0004
ABR/Derived Response						1.0000	1.0000	0.1153
MLR (10/s)							1.0000	0.2632

Note. Combined rank = sum of EPT-CPT, Clarity, and Reliability ranks.
Overall Friedman $\chi^2_r = 75.76$, _df_ = 7, $p < 0.00001$.

Figure Legends

Figure 1. Stimulus and recording apparatus. A: Filter setup for high-pass noise. B: Filter setup for notched noise. C: Setup for white noise.

Figure 2. Acoustic spectra of the tonal stimuli used in this study. Tones were generated by the TN 3000 system with the rise and fall times, and plateau durations indicated on the left. The tones were presented through a TDH-49 earphone at an intensity of 111 dB peak equivalent SPL. The acoustic waveforms were recorded using a 6-cc artificial ear (Brüel & Kjaer Type 4152 with a 4144 1-in microphone), amplified on a Brüel and Kjaer type 2619 preamplifier, and digitized on a TN 1500 signal averager. The average power spectral density function for each tone is plotted between 100 and 10,000 Hz using logarithmic intensity and frequency axes. The intensity axes are arbitrary.

Figure 3. Acoustic spectra of the 100-us click stimulus and noise used in this study. Generated by the TN 3000 system, the click was presented through a TDH-49 earphone at an intensity of 113 dB peak equivalent SPL. Broadband noise ("white noise") was generated by the Med Associates noise generator (model ANL-912) and presented through a TDH-49 earphone at an intensity of 100 dB SPL. Notched noise was obtained by band-reject filtering the white noise over a 1-octave range (Krohn-Hite model 3343, 48 dB/octave rolloff). The acoustic waveforms were recorded using

a 6-cc artificial ear (Brüel & Kjaer Type 4152 with a 4144 1-in microphone), amplified on a Brüel and Kjaer type 2619 preamplifier, and digitized on a TN 1500 signal averager. The average power spectral density functions for the click and for the noise are plotted between 100 and 10,000 Hz using logarithmic intensity and frequency axes. The intensity axes are arbitrary.

Figure 4. Derived brainstem responses. This figure shows the Derived Responses from one normal-hearing subject (#05). The intensities given on the left are those of the unmasked clicks. The frequencies given across the top represent the lower cut-off frequencies of the high-pass noise. With filter-slopes of 96 dB/octave this is the approximate center frequency of the effective narrow band stimulus. Responses for the 4000 - 8000 Hz band are represented by the 4000+ waveforms. In this and all subsequent figures, negativity recorded at the vertex is represented as an upward deflection. The wave Vs in the responses at each frequency at 70 dB nHL are indicated by the arrows. Clear wave Vs are not visible at the 500 Hz frequency band below 30 dB nHL in this subject. Latency of wave V increases with decreasing stimulus intensity and frequency.

Figure 5. Derived Response latency (wave V) as a function of stimulus intensity and frequency. Intensities given are those of the unmasked click. Datum points represent the average from at least five of the ten normal-hearing subjects. Wave V latency increases linearly with decreasing stimulus intensity,

and increases about 4 ms when the frequency band is decreased from 4000+ Hz to 500 Hz.

Figure 6. Derived Response amplitude (wave V) as a function of stimulus intensity and frequency. Intensities given are those of the unmasked click. Results are the average of data from ten normal-hearing subjects. No consistent difference exists between the amplitude results for the 500, 1000, and 2000 Hz bands. The 4000+ Hz band resulted in responses with greater amplitudes.

Figure 7. Brainstem responses to Clicks in Notched Noise. The better-than-average responses shown in this figure are from subject #13. The intensity of the broadband noise (no notch) was sufficient to mask the perceptual response of the subject. A notch was formed by band-reject filtering the noise over a 1-octave range, centered on the frequencies indicated at the top of this figure. Each tracing represents the average of 2000 trials. The responses to the 70-dB stimulus suggest an increase of wave V latency (indicated by the arrows) with decreasing stimulus frequency. Responses at the high-frequency bands show wave Vs at intensities down to 10-20 dB nHL. The waveforms recorded at the 500 and 1000 Hz bands, however, show interpretable wave Vs only at the highest intensities. Below 70 or 60 dB, the low-frequency responses contain peaks at latencies which appear inappropriate for the frequency and intensity of the effective stimulus.

Figure 8. Latency of brainstem response wave V to masked and unmasked 500 Hz tones. Each datum point represents the average results from a minimum of five of the ten normal-hearing subjects. NN = notched noise; WN = white noise. Intensity of the noise was 20 dB below the peak equivalent SPL of the tone. Wave V latency increases with decreasing stimulus intensity. The notch and white noise prolongs wave V latency at all stimulus intensities. The latencies of wave V to the 500 Hz tones in white noise are longer than when notched noise is used. This effect increases with decreasing stimulus intensity.

Figure 9. Latency of wave V to masked and unmasked 1000 Hz tones. Each datum point represents the average results from a minimum of five of the ten normal-hearing subjects. NN = notched noise; WN = white noise. Intensity of the noise was 20 dB below the peak equivalent SPL of the tone. Wave V latency increases with decreasing stimulus intensity. The notch and white noise prolongs wave V latency at stimulus intensities above 30 dB nHL, with this effect increasing with increasing stimulus intensity. The latencies of wave V to the 1000 Hz tones in white noise are longer than when notched noise is used.

Figure 10. Latency of wave V to masked and unmasked 2000 Hz tones. Each datum point represents the average results from a minimum of five of the ten normal-hearing subjects. NN = notched noise; WN = white noise. Intensity of the noise was 20 dB below the peak equivalent SPL of the tone. Wave V latency increases

with decreasing stimulus intensity. The notch noise prolongs wave V latency slightly at stimulus intensities above 40 dB nHL. At all stimulus intensities, latencies of wave V to the 2000 Hz tones in white noise are longer than when notched noise is used.

Figure 11. Latency of wave V to masked and unmasked 4000 Hz tones. Each datum point represents the average results from a minimum of five of the ten normal-hearing subjects. NN = notched noise; WN = white noise. Intensity of the noise was 20 dB below the peak equivalent SPL of the tone. Wave V latency increases with decreasing stimulus intensity. Little difference exists between the unmasked and notched noise functions. The white noise function demonstrates slightly longer latencies than both the masked and notched noise functions.

Figure 12. Amplitude of brainstem response wave V to masked and unmasked 500 Hz tones. The average results from the ten normal-hearing subjects are plotted. NN = notched noise; WN = white noise. Intensity of the noise was 20 dB below the peak equivalent SPL of the tone. Amplitude of wave V in response to the unmasked 500 Hz tones decreases with decreasing stimulus intensity. The use of noise masking markedly decreases amplitude of wave V at higher stimulus intensities. Little difference exists, however, between the masked and unmasked response amplitudes at low stimulus intensities. At 30 dB nHL and higher, responses to tones in white noise have lower amplitudes than those to tones in notched noise.

Figure 13. Amplitude of wave V to masked and unmasked 1000 Hz tones. The average results from the ten normal-hearing subjects are plotted. NN = notched noise; WN = white noise. Intensity of the noise was 20 dB below the peak equivalent SPL of the tone. Amplitude of wave V in response to the unmasked 1000 Hz tones decreases with decreasing stimulus intensity. The use of noise masking markedly decreases amplitude of wave V at higher stimulus intensities. Little difference exists, however, between the masked and unmasked response amplitudes at low stimulus intensities. Above 20 dB nHL, responses to tones in white noise show lower amplitudes than those to tones in notched noise.

Figure 14. Amplitude of wave V to masked and unmasked 2000 Hz tones. The average results from the 10 normal-hearing subjects are plotted. NN = notched noise; WN = white noise. Intensity of the noise was 20 dB below the peak equivalent SPL of the tone. Amplitude of wave V in response to the unmasked 2000 Hz tones decreases with decreasing stimulus intensity. The use of noise masking markedly decreases amplitude of wave V at higher stimulus intensities. Little difference exists, however, between the masked and unmasked response amplitudes at low stimulus intensities. At all intensities, the responses to tones in white noise show lower amplitudes than those to tones in notched noise.

Figure 15. Amplitude of wave V to masked and unmasked 4000 Hz tones. The average results from the ten normal-hearing subjects

are plotted. NN = notched noise; WN = white noise. Intensity of the noise was 20 dB below the peak equivalent SPL of the tone. Amplitude of wave V in response to the unmasked 4000 Hz tones decreases with decreasing stimulus intensity. The use of noise masking markedly decreases amplitude of wave V at higher stimulus intensities. No difference exists, however, between the masked and unmasked response amplitudes below 30 dB nHL. Above 30 dB nHL, the responses to tones in white noise are slightly lower amplitudes than those to tones in notched noise.

Figure 16. Latency of MLR component Pa as a function of stimulus intensity and frequency. Each datum point represents the average data from at least five of the ten normal-hearing subjects. Less than five subjects showed replicable responses to the 4000 Hz stimulus when presented at levels below 50 dB nHL. Decreasing stimulus frequency resulted in longer Pa latencies. Only small and inconsistent latency increases occur with decreasing stimulus intensity.

Figure 17. Amplitude of the MLR component Pa as a function of stimulus intensity and frequency. Stimulus presentation rate was 9.6 per second. The EEG was filtered using a 10 - 1500 Hz bandpass (12 dB/octave). Amplitude was measured to the preceeding vertex-negative peak (Na). Each datum point plotted represents the average data from ten normal-hearing subjects. Less than five subjects showed replicable responses to the 4000 Hz stimulus presented at levels below 50 dB nHL. Small decreases in Pa

amplitude occur as stimulus intensity is decreased, with a tendency for the lower-frequency stimuli to elicit larger responses.

Figure 18. The 40-Hz steady state potential. The 40-Hz responses from one subject (#04) are presented in this figure. Each tracing represents the average of 2000 trials. The tones (5 ms rise and fall; 5 ms plateau) were presented at a rate of 39/s. The EEG was filtered using a 10 - 1500 bandpass (12 dB/octave). The resulting sinusoidal response decreases in amplitude down to threshold, and is larger for low-frequency stimuli.

Figure 19. Amplitude of the 40-Hz steady state potential as a function of stimulus intensity and frequency. Results represent the average data from the ten normal-hearing subjects. The largest peak-to-peak amplitude present in the waveforms was recorded as the amplitude. Average noise levels were estimated to be 0.25 uV. This noise level was obtained by recording the largest peak-to-peak amplitude present in these subjects' non-response waveforms (at 0 or -10 dB nHL). Amplitude of the 40-Hz response decreases linearly with decreasing stimulus intensity. Increasing stimulus frequency results in smaller amplitudes.

Figure 20. Slow Responses. Shown are the Slow Responses from a normal-hearing subject (#11). Component N1 is indicated by the arrow for the 1000 Hz response at 70 dB nHL. Latency of this

component increases, and its amplitude decreases, with decreasing stimulus intensity. Responses from this subject are visible at 20 dB nHL for the 500, 1000, and 2000 Hz tones, and at 30 dB nHL for the 4000 Hz tone.

Figure 21. Latency of the Slow Response (N1) as a function of stimulus intensity and frequency. Datum points represent the mean results from at least five of the ten normal-hearing subjects. Below 30 dB nHL fewer than five subjects showed replicable Slow Responses to the 2000 and 4000 Hz stimuli. Latency of N1 increases slowly with decreasing stimulus intensity until near threshold, at which point latency rapidly increases. No clear relationship is evident between stimulus frequency and N1 latency.

Figure 22. Amplitude of the Slow Response (N1) as a function of stimulus intensity and frequency. Amplitude was measured between the N1 peak and the following positive peak (P2). Results are the average of data from the ten normal-hearing subjects. Amplitude decreases linearly with decreasing stimulus intensity. Low-frequency stimuli elicit slightly larger responses.

Figure 23. Derived brainstem responses from subject #52. This figure shows the 1000 and 4000+ Hz Derived Responses from a patient with a low-frequency sensorineural hearing loss. The 4000+ Hz responses indicate a threshold of 10 dB nHL (indicated by the star) which is within 10 dB of her 5 and 15 dB pure tone

HLs for 4000 and 8000 Hz. The 1000 Hz response threshold of 40 dB is within 5 dB of her pure tone HL. The Derived Responses thus mapped threshold. The 1000 Hz responses, however, show considerable variability, with the response disappearing at 60 dB, and subsequently reappearing at 50 and 40 dB nHL.

Figure 24. Left: Temporary threshold shift (TTS) following exposure to noise levels used to mask clicks. This figure shows the audiogram obtained (a) prior to subject #52's participation in the study; (b) one day following her participation in the ABR/Derived Response test; and (c) three days following her exposure to the noise in the Derived Response test. Following her participation, she developed tinnitus which was centered around 1000 Hz. The pure tone audiometry performed one day after her exposure showed a 30-dB TTS at 4000 Hz. When retested at 3 days post-exposure, her thresholds had returned to her pre-exposure levels, and her tinnitus had disappeared. In this subject we had used 118 dB SPL noise (broadband) to mask the 90 dB nHL clicks; the maximum click intensity was subsequently lowered to 80 dB nHL for all other individuals. Right: Subject #52's brainstem responses to unmasked clicks show a low threshold and a normal latency-intensity function, suggesting normal sensitivity at high frequencies. This should perhaps have indicated the need for caution when using the derived-response technique in this patient. Each tracing represents the average of 2000 trials. Click intensity in dB nHL is shown to the left of the responses.

Figure 25. The effects of a flat conductive loss on brainstem response latency-intensity functions. The left of this figure shows the normal latency-intensity functions for the brainstem responses to unmasked clicks and unmasked 4000, 2000, 1000, and 500 Hz tones. The results were obtained from ten normal-hearing subjects. Latency increases with decreasing stimulus frequency and intensity. The increase seen with decreasing intensity is greater for the low-frequency stimuli. The right of this figure shows the latency-intensity functions obtained from a patient with a 45 to 55 dB flat conductive loss (subject #32). These functions are shifted up and to the right (compare the intensity scales).

Figure 26. Variability of the Transient Middle Latency Responses. This figure shows the MLRs to 500 and 1000 Hz tones recorded from a subject (#33) with a sloping high-frequency loss. This subject's pure tone HL for 500 and 1000 Hz are indicated in the brackets under the titles. Each MLR waveform represents the average of 500 trials. The EEG was filtered using a bandpass of 10 - 1500 Hz (12 dB/oct). Intensities of the stimuli (in dB nHL) are indicated to the left of each recording. Response threshold is indicated by the star. At 500 Hz, the MLR overestimated threshold by 35 dB. The waveforms are quite variable, and even though there is some suggestion of responses to the 500 Hz tones at lower intensities, the replicability is so poor that the raters scored them as non-responses. Furthermore, at both frequencies it is difficult to differentiate some waveforms

recorded in response to stimuli which should be below threshold from those recorded in response to high-intensity stimuli.

Figure 27. Wave V superimposed on the 40-Hz response. This figure shows the brainstem responses to unmasked 500 Hz tones from a subject with normal hearing (#02), and from a subject with a low-frequency conductive hearing loss (#34). The 500 Hz pure tone HL for each subject is indicated at the top of the tracings. Intensity of the 500 Hz tone is shown on the left of each set of tracings. Responses represent the average of 2000 trials each. Response threshold is indicated by the star. A 39/s stimulus repetition rate was used to record the brainstem responses. This rate resulted in wave V of the brainstem response (indicated by the filled triangles) to be superimposed on the 40-Hz sinusoid. Separate from the 40-Hz response at high intensities, wave V becomes indistinct below 40 - 50 dB nHL in the normal-hearing subject (a questionable wave V is indicated by the open triangle) and below 80 dB nHL in the patient. The 40-Hz sinusoid, however, remains visible down to threshold.

Figure 28. The effects of amplitude recruitment. The brainstem, 40-Hz, and Slow responses to 500 Hz tones from subject #35 are shown in this figure. This subject had a flat sensorineural loss (45 to 75 dB HL), and stapedial reflex thresholds of 100 and 110 dB HL for 1000 and 4000 Hz. Evoked potential thresholds are indicated by the stars. The brainstem and 40-Hz responses are large and clear down to and including 60

dB nHL, with amplitudes of 0.80 uV at this intensity. Below this intensity they disappear completely. This rapid decline in amplitude over a 10-dB change in intensity is not seen in the normal ear and is indicative of amplitude recruitment. The phenomenon of amplitude recruitment aids threshold determination in this and many other patients with sensorineural hearing loss. The Slow Responses from this subject, on the other hand, are noisy, disappear earlier, and do not demonstrate recruitment. Furthermore, at 40 dB nHL -- well below this subject's behavioral threshold -- the background noise in the two replications superimposes, resulting in waveforms which appear to contain a response.

Figure 29. Effects of a steep high-frequency hearing loss on the click-evoked brainstem response. The left of this figure shows the brainstem responses to unmasked clicks from subject #37. Each tracing is the average of 2000 trials. These responses show a normal wave V latency at high click intensities, and a normal threshold at 20 dB nHL. Wave V latency to low-intensity clicks, however, is prolonged. These changes are shown in the wave V latency-intensity function for this subject, shown on the right. Wave latency is within normal limits (dashed lines indicate ± 2 standard deviations) down to 50 dB nHL. Below this intensity, however, a large jump to latencies well outside of the normal limits occurs.

Figure 30. Derived brainstem responses from subject #37. The

500 and 2000 Hz Derived Responses from this subject provide insight into the cause of the "recruitment" of latency seen with the unmasked responses. The high-intensity 2000 Hz Derived Responses are similar in morphology to the high-intensity unmasked responses, and show a wave V latency within normal limits for this frequency band (see Figure 5). Wave V (indicated by the filled triangles) is clearly visible in the 80, 70, and 60 dB nHL responses. The response then disappears, reappearing at 40 dB nHL with a questionable wave V (indicated by the open triangle). Response threshold (shown by the star) underestimated pure tone threshold by 15 dB. This was probably due to the variability of the Derived Responses. Wave V latencies for the 500 Hz responses were also within the normal range (Figure 5). The morphology of these responses, particularly at lower intensities, is similar to the morphology of the low-intensity responses to the unmasked clicks. Indeed, the 500 Hz Derived Responses at 40 and 30 dB nHL are nearly identical to the responses to the unmasked clicks presented at these intensities. The Derived Responses from this subject suggest that the abnormal jump in the unmasked wave V latency is due to a change in the cochlear origin of this response.

Figure 31. Brainstem responses to unmasked and masked 2000 Hz tones: Subject 37. Subject #37's brainstem responses to 2000 Hz tones presented alone (TONE) and in notched noise (TONENN) are shown in this figure. Each waveform represents the average of 2000 trials. Response thresholds are indicated by the stars. The

responses to the unmasked tones underestimate her 55 dB pure tone threshold at for 2000 Hz by 15 dB. This underestimation is probably due to the spread of the tone to the more-sensitive 1000 Hz region. The addition of notched noise masks this region and results in a 10-dB improvement in threshold prediction.

Figure 32. The postauricular muscle response. This figure shows the Transient Middle Latency Responses (10/s) and the 40-Hz Steady State Responses (39/s) from subject #39. The tonal frequency of the stimulus was 4000 Hz. Waveforms represent the average of 500 and 2000 trials each at 10/s and 39/s respectively. Response thresholds are indicated by the stars. The 10/s response in this subject shows a very large postauricular muscle response (indicated by filled triangle), particularly in response to the 70 dB stimulus. The 40-Hz Response to the 70 dB stimulus is unusual in morphology and has a peak-to-peak amplitude which is twice the mean from the normal-hearing subjects. The unusual morphology and large amplitude is perhaps due to the presence of a postauricular muscle response in these waveforms (open triangle). The 40-Hz Responses shown in this figure also demonstrate amplitude recruitment.

Figure 33. 40-Hz Steady State Potentials in a patient with a significant mid-frequency hearing loss. The 40-Hz responses from subject #40 are shown in this figure. Each tracing represents the average of 2000 trials. Thresholds are indicated by the stars. Pure tone behavioral thresholds for each frequency are indicated

in brackets under the titles. The 40-Hz responses predict within 5 dB of the behavioral thresholds.

Figure 34. Subject #40's mid-frequency hearing loss, the extent of which is shown by the audiogram on the left of this figure, did not result in any abnormalities in his brainstem responses to unmasked clicks. These responses, shown on the right of this figure, demonstrate normal response morphology, normal wave V latencies, and normal threshold (30 dB nHL).

Figure 35. Brainstem responses to clicks and tones in notched noise (subject #40). Each tracing represents the average of 2000 trials. Response thresholds are indicated by the stars. The intensity required to mask 70 dB nHL clicks was 98 dB SPL while the intensity of noise used for the masking of the 70 dB nHL tones was 76 dB SPL. The right of the figure shows subject #40's responses to 500 and 2000 Hz tones in notched noise (TONENN). The left of the figure shows his responses to clicks in 500 and 2000 Hz notched noise (CLICKNN). Even with extra replications, the responses to clicks in notched noise in this subject are difficult to detect, and very small when present. At 60 dB nHL, the 500 Hz response shows what may be a small wave V (indicated by the open triangle) superimposed on a 40-Hz sinusoid. No replicable responses were visible below this level. Threshold at 500 Hz was therefore overestimated by 40 dB. The 2000 Hz waveforms are even noisier, with threshold recorded at 70 dB. On the other hand, subject #40's responses to tones in

notched noise are clear and have relatively large amplitudes. The large 40-Hz sinusoidal response to the 500 Hz tones aids threshold determination, predicting threshold within 10 dB of his pure tone threshold. The 2000 Hz tonal responses do not show the large 40-Hz sinusoid but threshold is accurately predicted.

Figure 36. Evoked potential Ratings. Example waveforms from the ABR/Tones in Notched Noise (ABR/TONENN), the Transient Middle Latency (MLR(10/s)), and the Slow Response (SLOW) EP tests are presented in this figure. Waveforms with combined ratings of 4, 3, 2 and 1 are shown. The subject from whom a waveform was recorded and the stimulus intensity and frequency are indicated for each example. The scores given by the two raters are given in brackets. These ratings were combined to obtain the ratings shown on the far left of the figure. A rating of "4" indicates a "definite response", a "3" means a "probable response", a "2" indicates a "probable non-response", and a "1" indicates a "definite non-response".

Figure 37. Test accuracy: 500 Hz. EPT-CPT is the difference between EP threshold and pure tone behavioral threshold. The closer a result is to 0 dB, the greater is the test's accuracy. Test codes: 01 = ABR/Derived Responses; 02 = ABR/Clicks in Notched Noise; 03 = ABR/Tones; 04 = ABR/Tones in Notched Noise; 05 = ABR/Tones in White Noise; 06 = Transient Middle Latency Response; 07 = 40-Hz Steady State Potential; 08 = Slow Response. The Tukey $HSD_{0.05}$ = 9.3 dB.

Figure 38. Test accuracy: 1000 Hz. EPT-CPT is the difference between EP threshold and pure tone behavioral threshold. The closer a result is to 0 dB, the greater is the test's accuracy. Test codes: 01 = ABR/Derived Responses; 02 = ABR/Clicks in Notched Noise; 03 = ABR/Tones; 04 = ABR/Tones in Notched Noise; 05 = ABR/Tones in White Noise; 06 = Transient Middle Latency Response; 07 = 40-Hz Steady State Potential; 08 = Slow Response. The Tukey $HSD_{0.05} = 9.3$ dB.

Figure 39. Test accuracy: 2000 Hz. EPT-CPT is the difference between EP threshold and pure tone behavioral threshold. The closer a result is to 0 dB, the greater is the test's accuracy. Test codes: 01 = ABR/Derived Responses; 02 = ABR/Clicks in Notched Noise; 03 = ABR/Tones; 04 = ABR/Tones in Notched Noise; 05 = ABR/Tones in White Noise; 06 = Transient Middle Latency Response; 07 = 40-Hz Steady State Potential; 08 = Slow Response. The Tukey $HSD_{0.05} = 9.3$ dB.

Figure 40. Test accuracy: 4000 Hz. EPT-CPT is the difference between EP threshold and pure tone behavioral threshold. The closer a result is to 0 dB, the greater is the test's accuracy. Test codes: 01 = ABR/Derived Responses; 02 = ABR/Clicks in Notched Noise; 03 = ABR/Tones; 04 = ABR/Tones in Notched Noise; 05 = ABR/Tones in White Noise; 06 = Transient Middle Latency Response; 07 = 40-Hz Steady State Potential; 08 = Slow Response. The Tukey $HSD_{0.05} = 9.3$ dB.

Figure 41. Test accuracy: Overall. Results are collapsed across group (normal-hearing and hearing-impaired) and frequency (500, 1000, 2000 & 4000 Hz). The closer a result is to 0 dB, the greater is the test's accuracy. EPT-CPT is the difference between EP threshold and pure tone behavioral threshold. Test codes: 01 = ABR/Derived Responses; 02 = ABR/Clicks in Notched Noise; 03 = ABR/Tones; 04 = ABR/Tones in Notched Noise; 05 = ABR/Tones in White Noise; 06 = Transient Middle Latency Response; 07 = 40-Hz Steady State Potential; 08 = Slow Response. The Tukey $HSD_{0.05}$ = 9.3 dB.

Figure 42. Overall response clarity. Results are collapsed across group (normal-hearing and hearing-impaired) and frequency (500, 1000, 2000 & 4000 Hz). Response clarity was obtained by calculating the mean combined rating at and above threshold and subtracting from it the mean combined rating below threshold. Test codes: 01 = ABR/Derived Responses; 02 = ABR/Clicks in Notched Noise; 03 = ABR/Tones; 04 = ABR/Tones in Notched Noise; 05 = ABR/Tones in White Noise; 06 = Transient Middle Latency Response; 07 = 40-Hz Steady State Potential; 08 = Slow Response. The Tukey $HSD_{0.05}$ = 0.37.

Figure 43. Overall inter-rater reliability. Results are collapsed across group (normal-hearing and hearing-impaired) and frequency (500, 1000, 2000 & 4000 Hz). This measure was obtained by calculating the absolute difference between the ratings provided

by the two raters. The lower the disagreement the better the reliability. Test codes: 01 = ABR/Derived Responses; 02 = ABR/Clicks in Notched Noise; 03 = ABR/Tones; 04 = ABR/Tones in Notched Noise; 05 = ABR/Tones in White Noise; 06 = Transient Middle Latency Response; 07 = 40-Hz Steady State Potential; 08 = Slow Response. The Tukey $HSD_{0.05} = 0.19$.

Figure 1

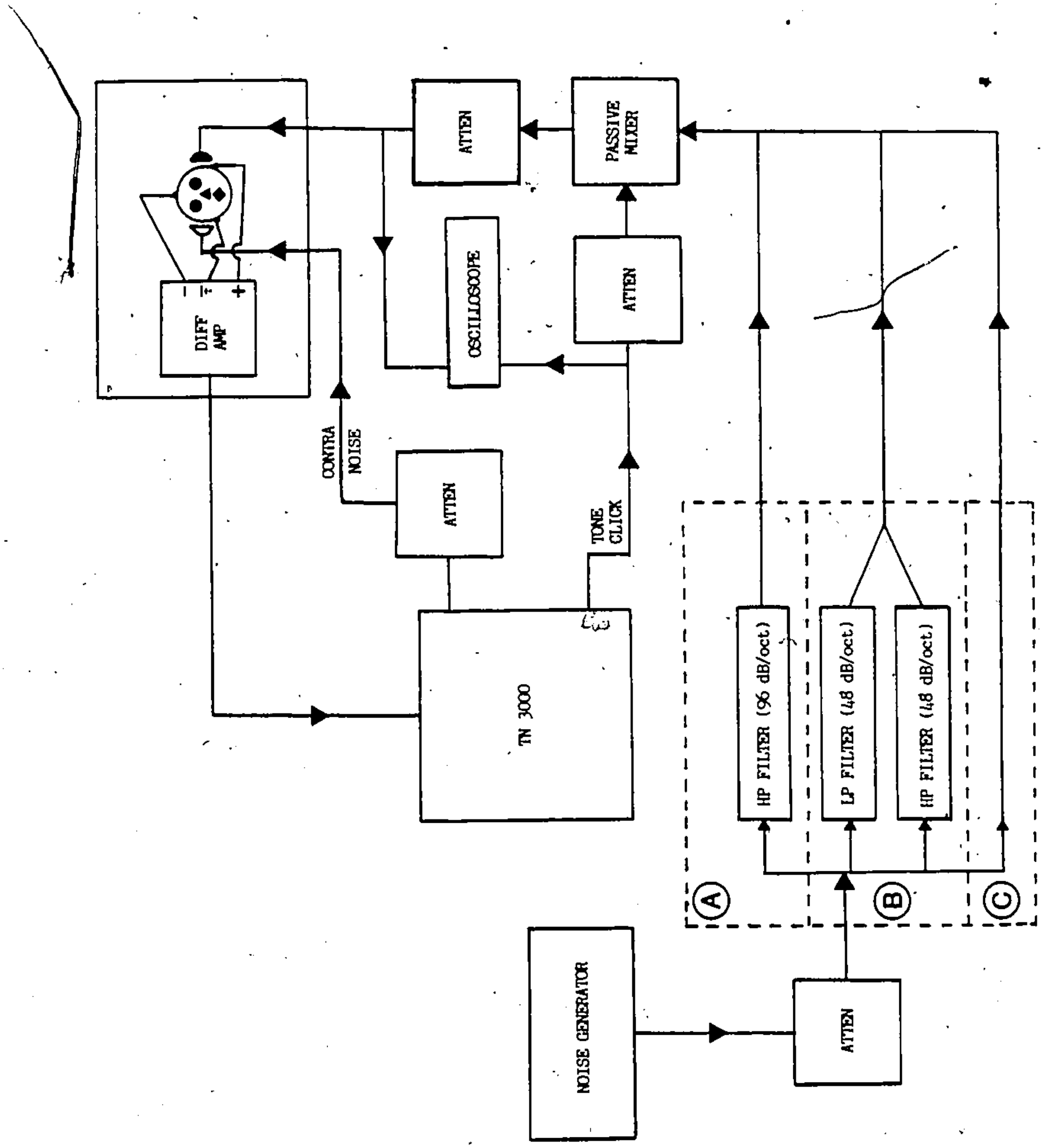

ATTEN
PASSIVE MIXER
ATTEN
OSCILLOSCOPE
−
+
DIFF AMP
CONTRA NOISE
ATTEN
TONE CLICK
TN 3000
HP FILTER (96 dB/oct)
LP FILTER (48 dB/oct)
HP FILTER (48 dB/oct)
A
B
C
NOISE GENERATOR
ATTEN

Figure 2

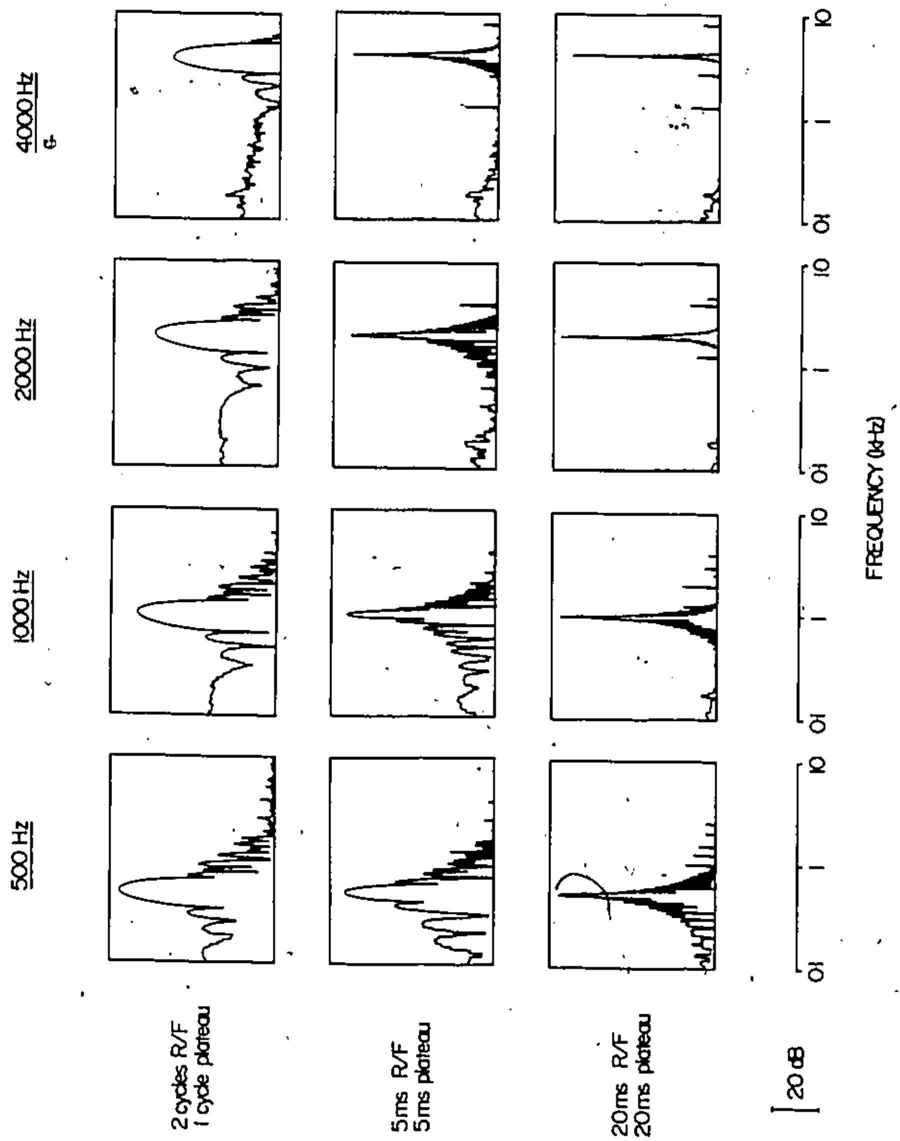

500 Hz
1000 Hz
2000 Hz
4000 Hz
2 cycles R/F
1 cycle plateau
5ms R/F
5ms plateau
20ms R/F
20ms plateau
20 dB
.1
1
10
FREQUENCY (kHz)

Figure 3

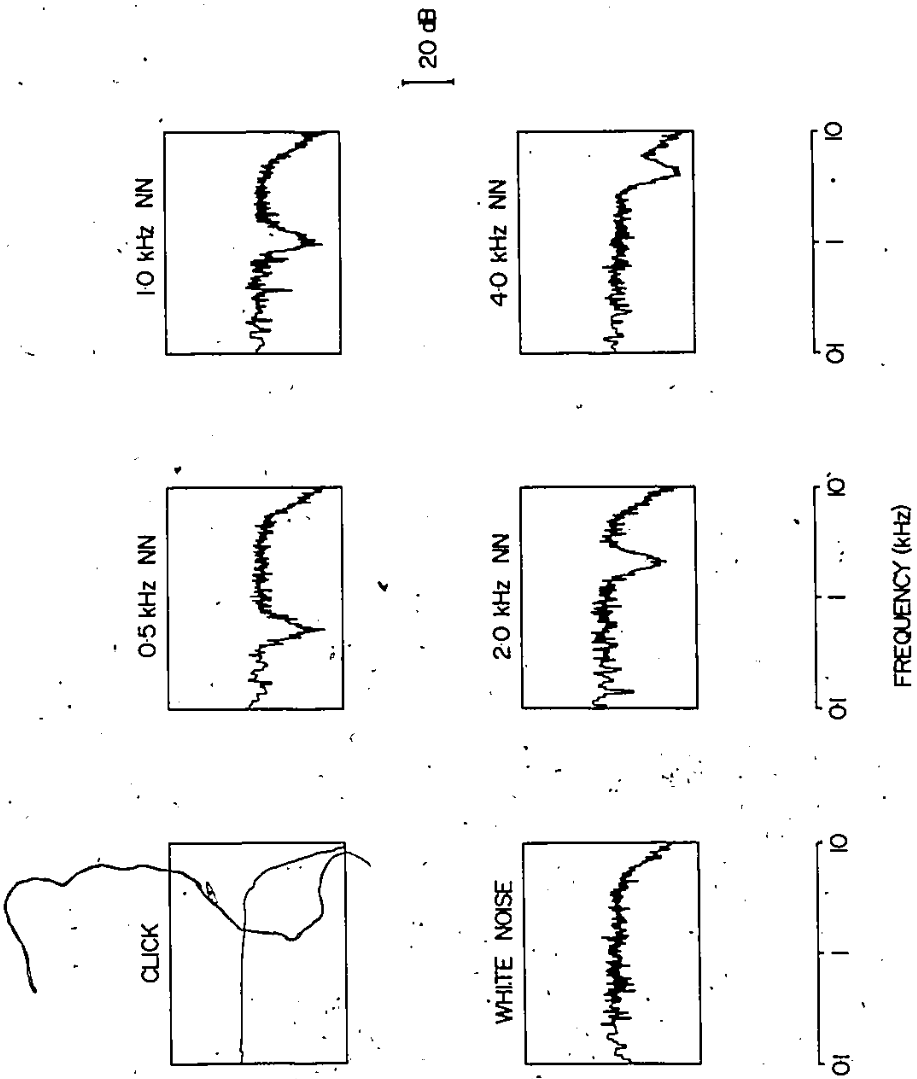

20 dB
1.0 kHz NN
4.0 kHz NN
0.5 kHz NN
2.0 kHz NN
CLICK
WHITE NOISE
0.1
1
10
FREQUENCY (kHz)

Figure 4

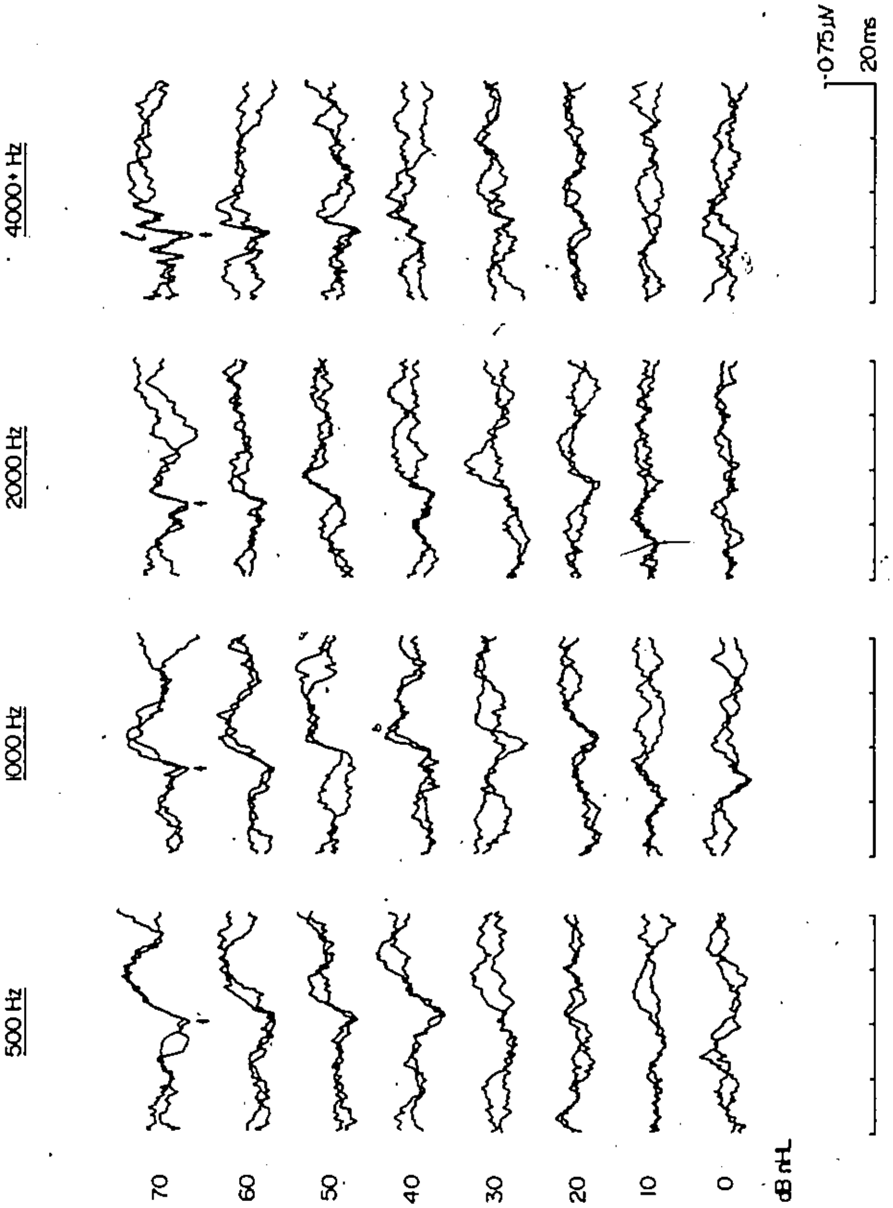

4000+ Hz
2000 Hz
1000 Hz
500 Hz
0.75µV
20ms
70
60
50
40
30
20
10
0
dB nHL

Figure 5

DRS 13/10/83

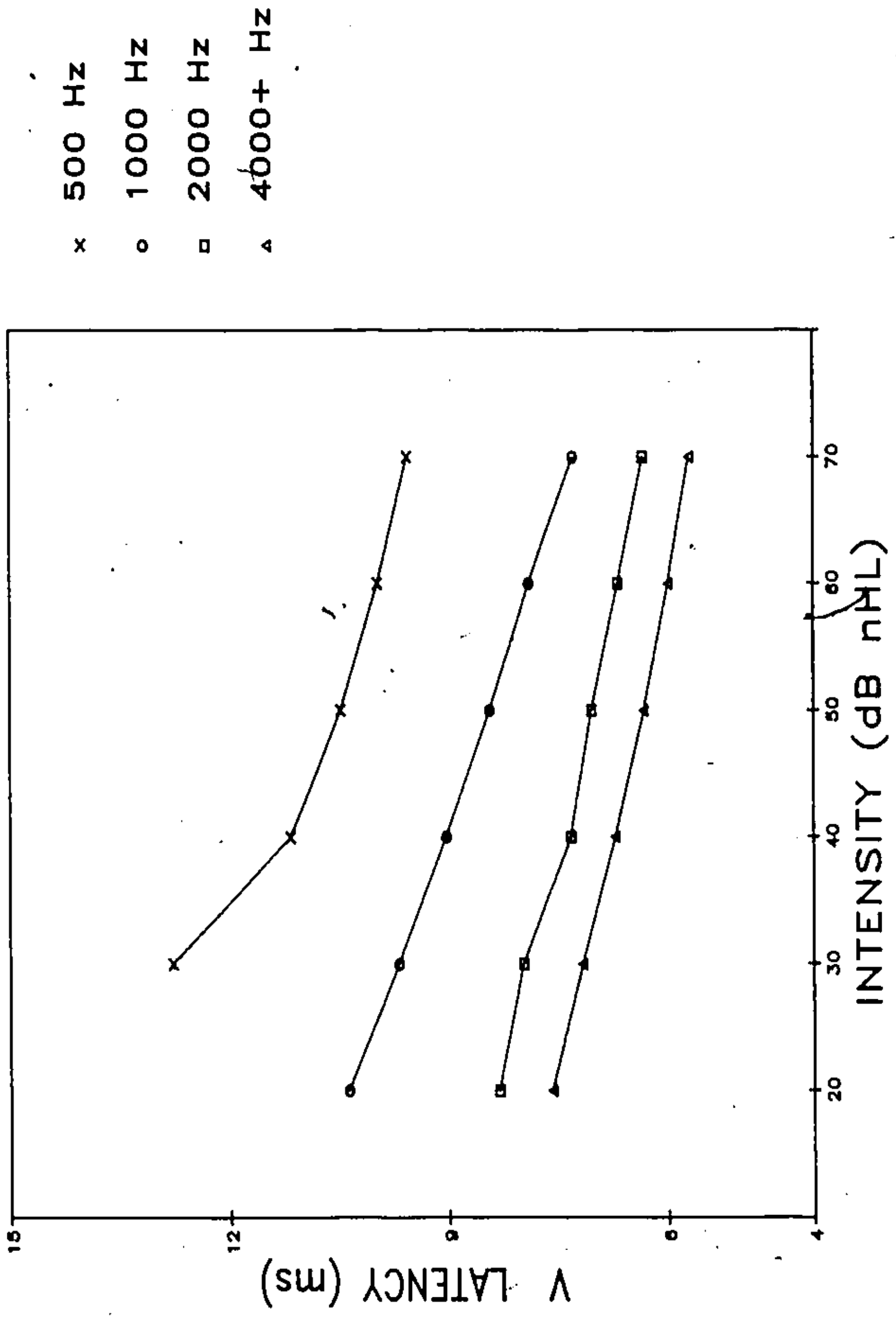
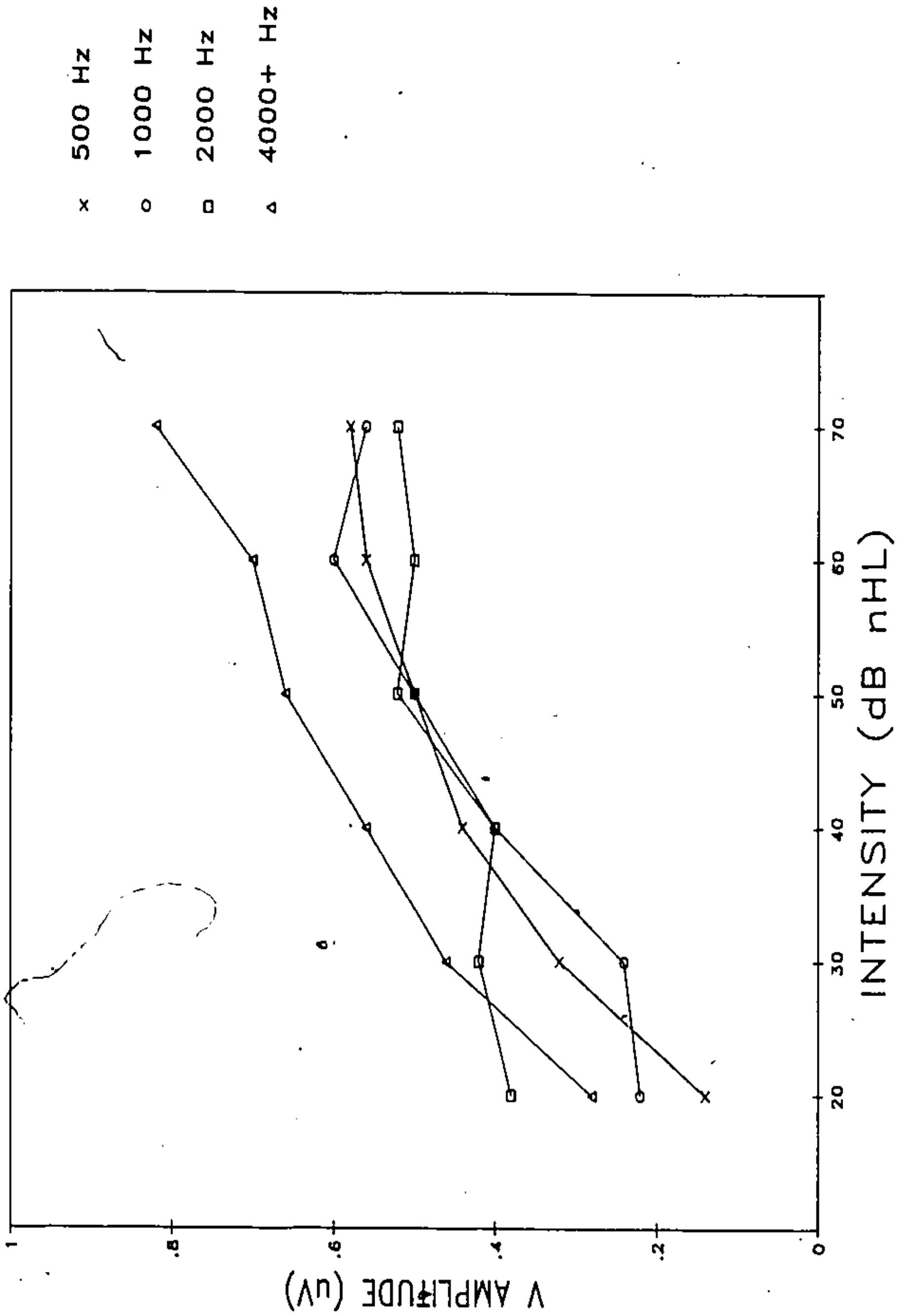


Figure 6



DRS 10/12/83

Figure 7

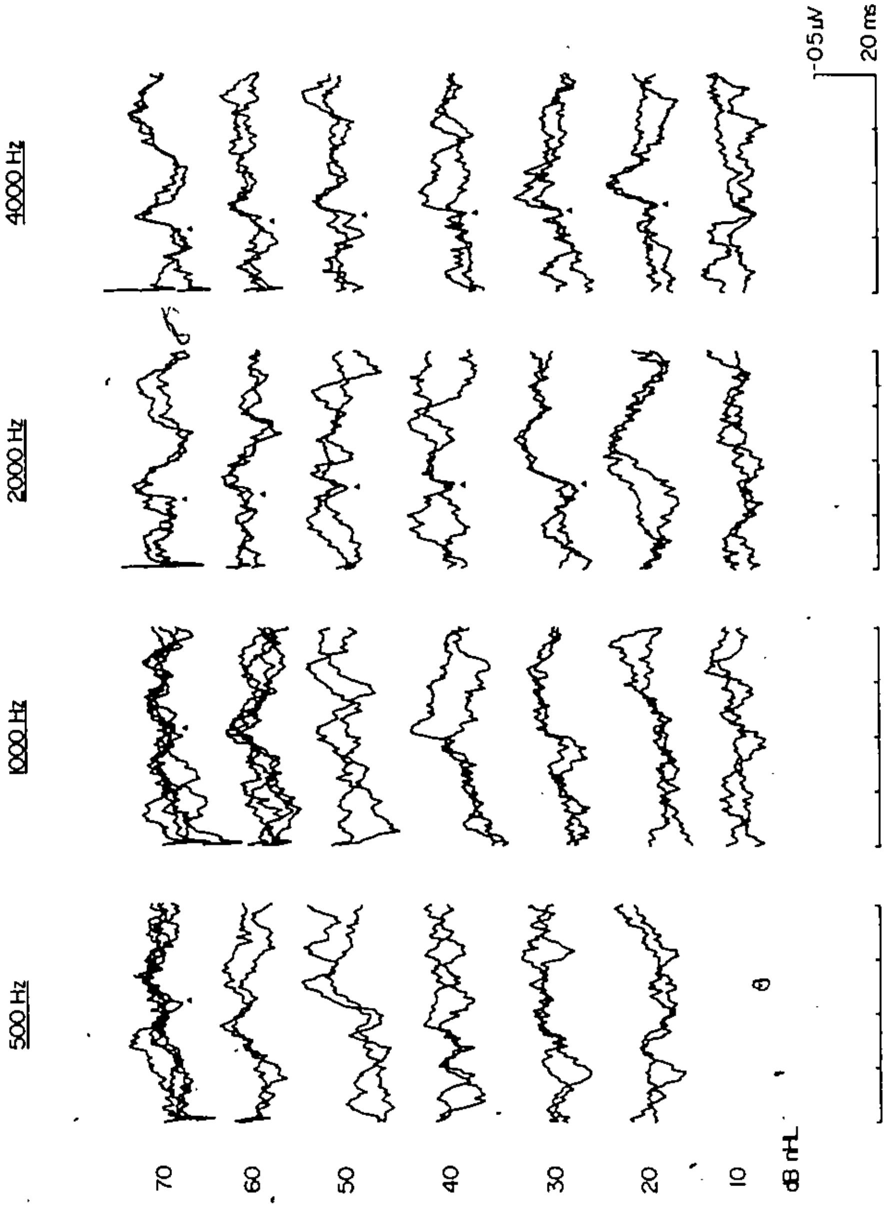
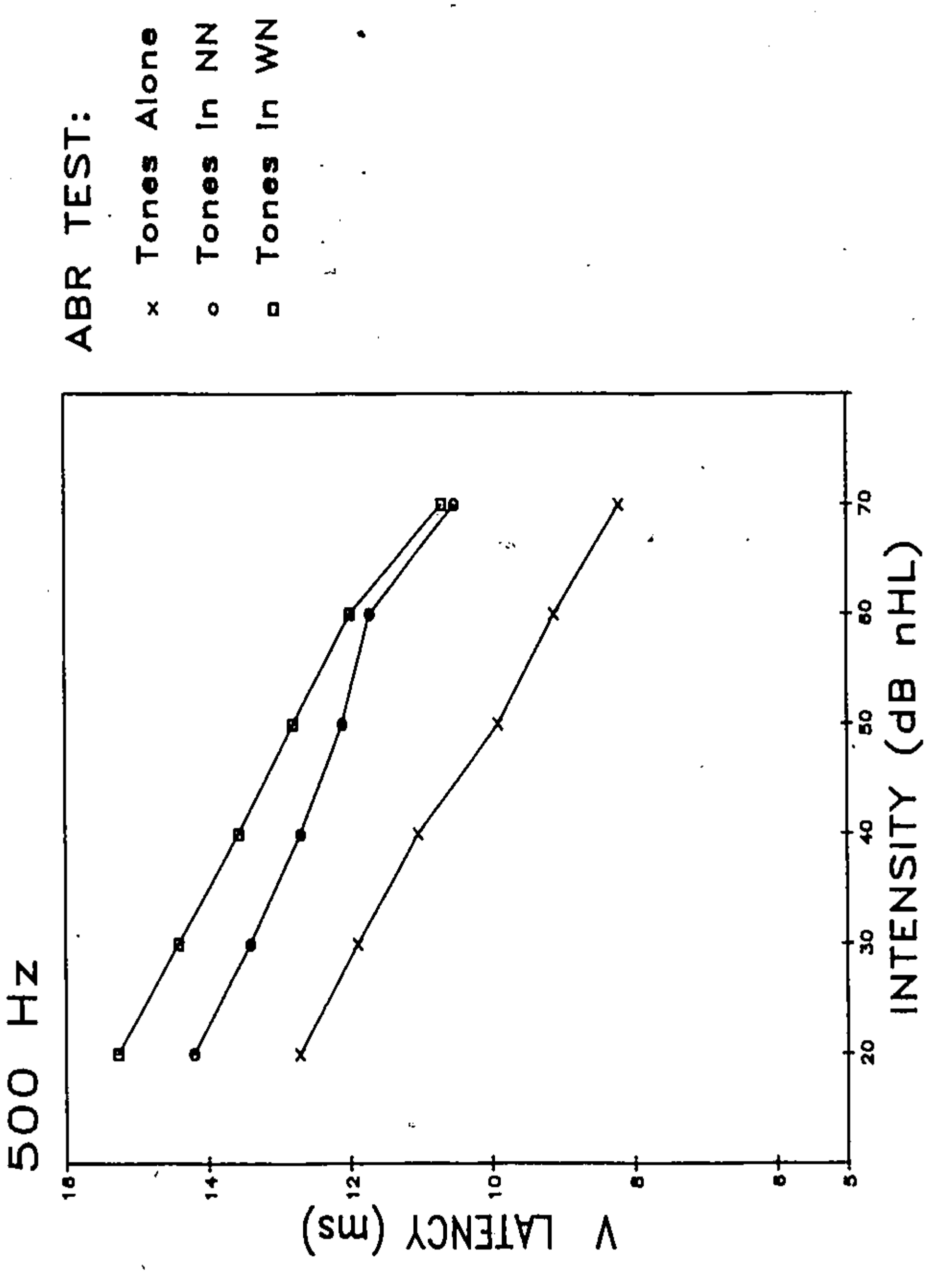
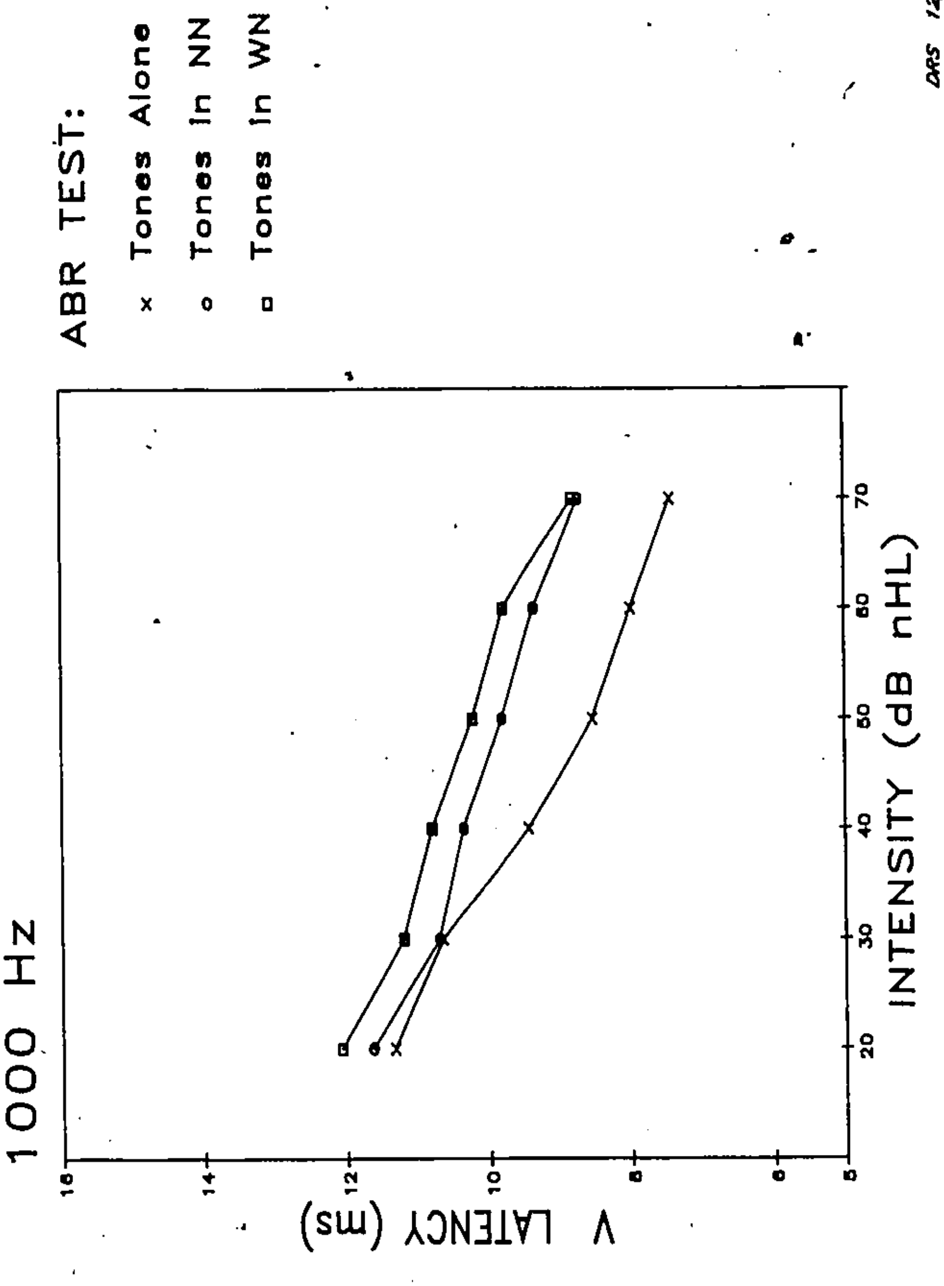

500 Hz
1000 Hz
2000 Hz
4000 Hz
70
60
50
40
30
20
10
dB nHL
0.5 µV
20 ms

Figure 8



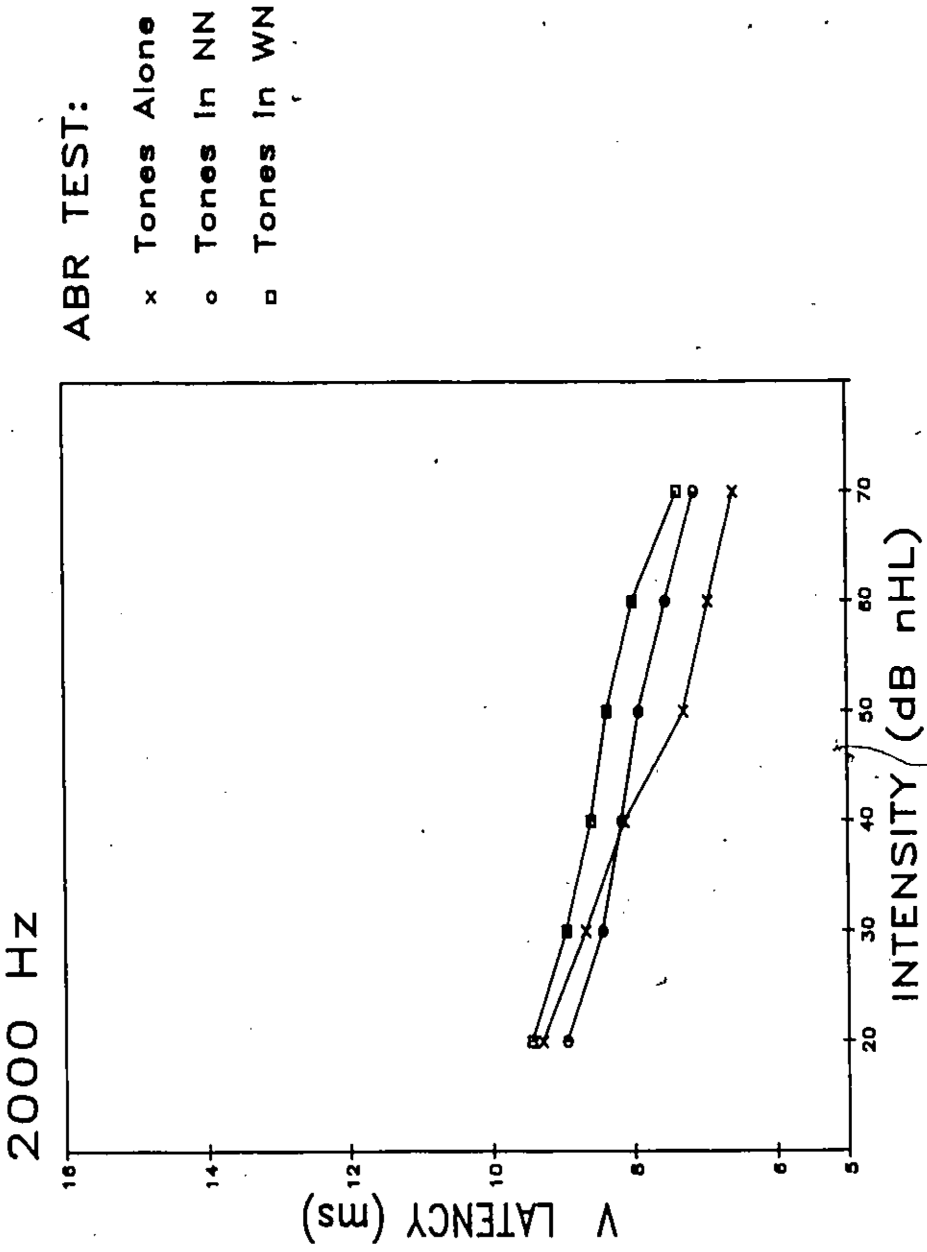
DRS 12/10/83

Figure 9



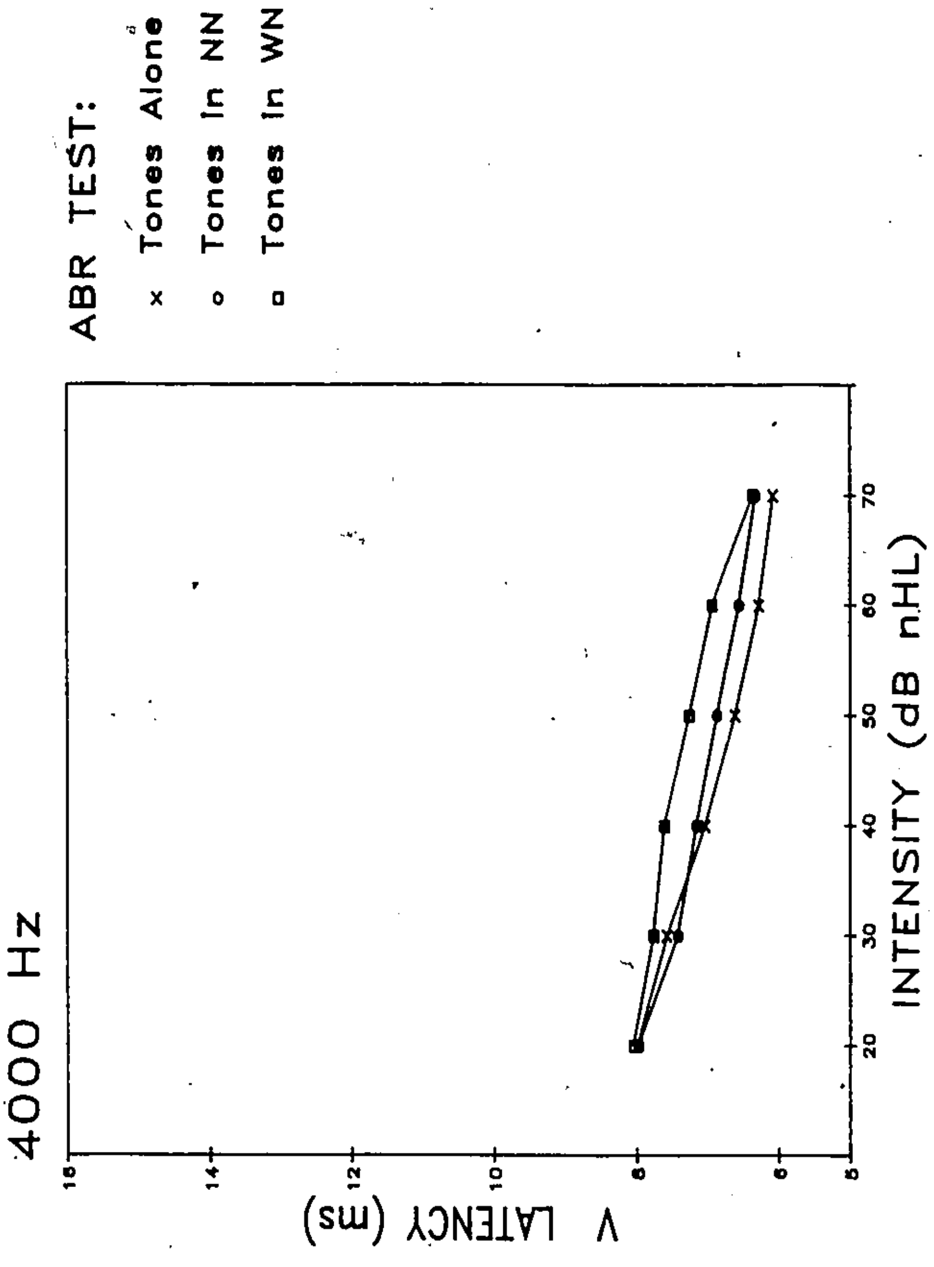
DRS 12/10/83

Figure 10



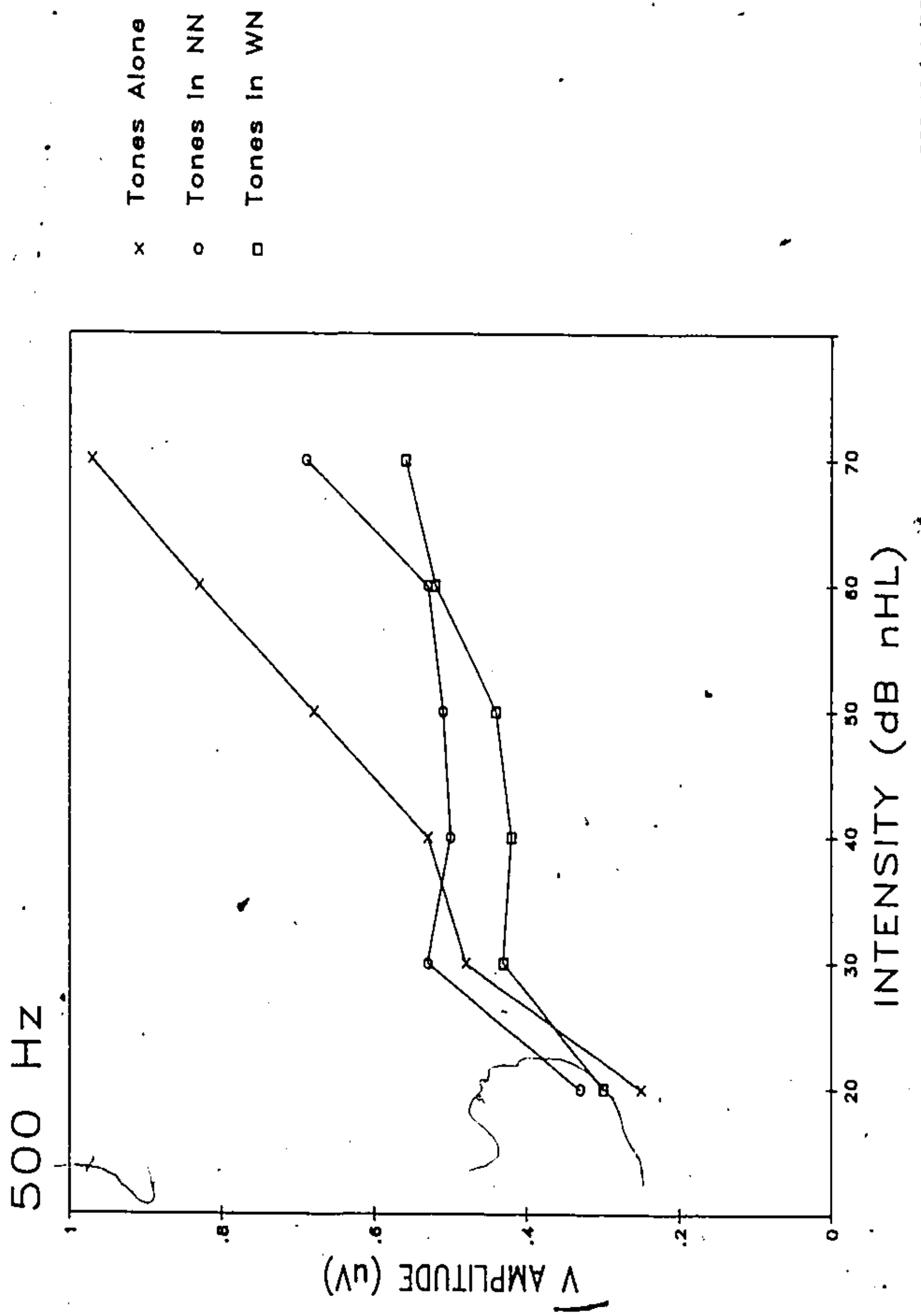
DRS 12/10/83

Figure 11



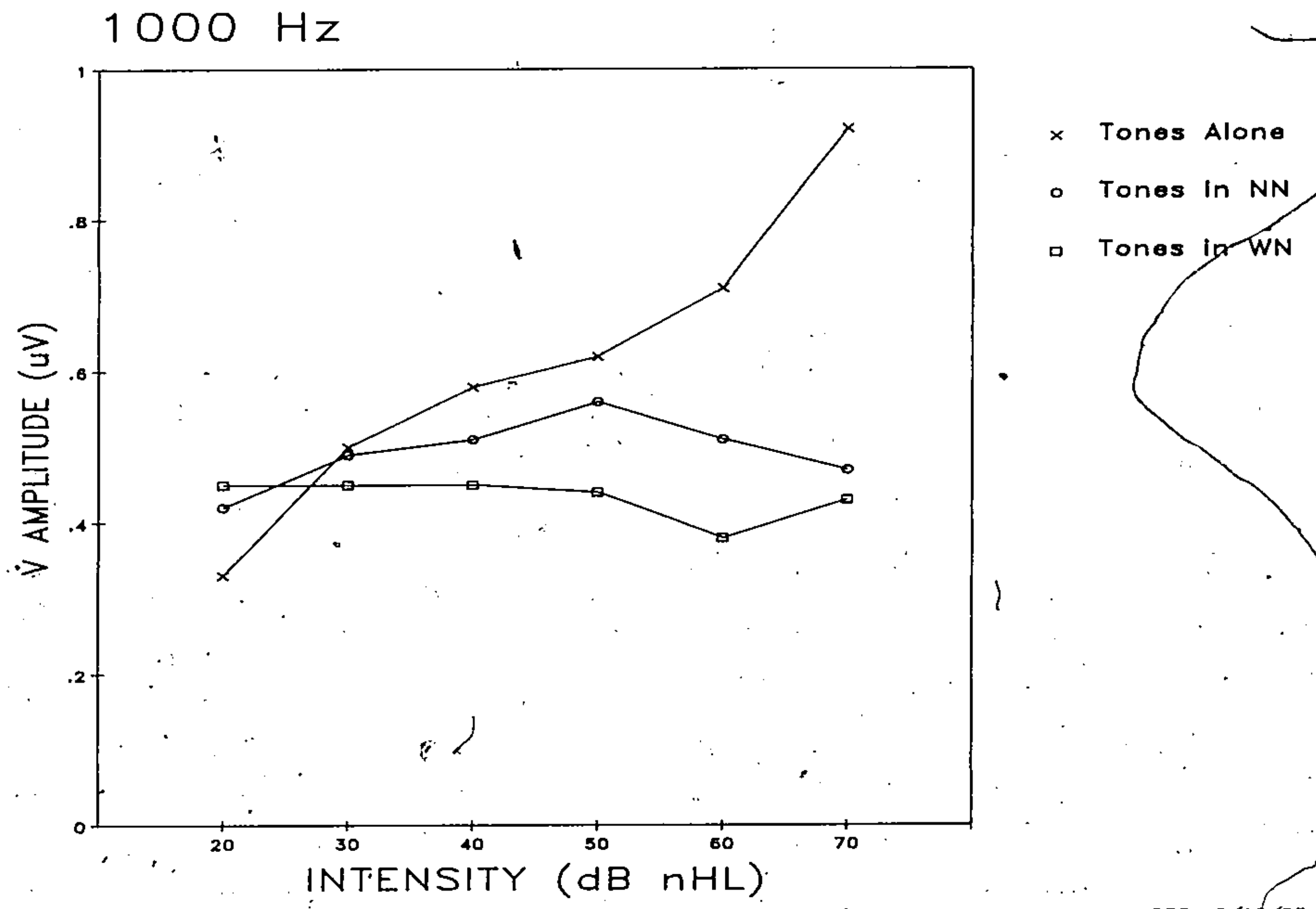
DRS 12/10/83

Figure 12



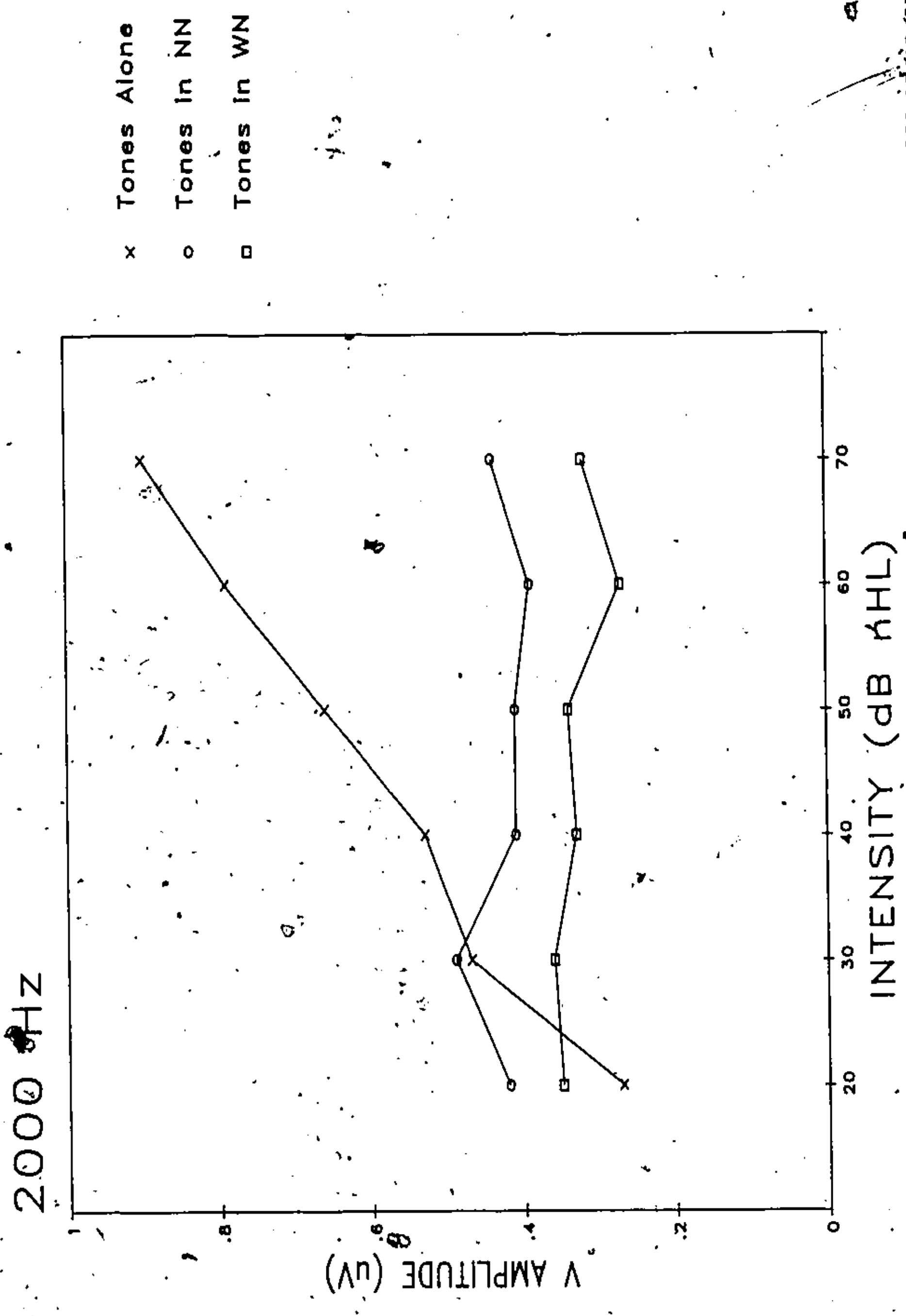
DRS 10/12/83

Figure 13



DRS 10/12/83

Figure 14



DRS 10/12/83

Figure 15

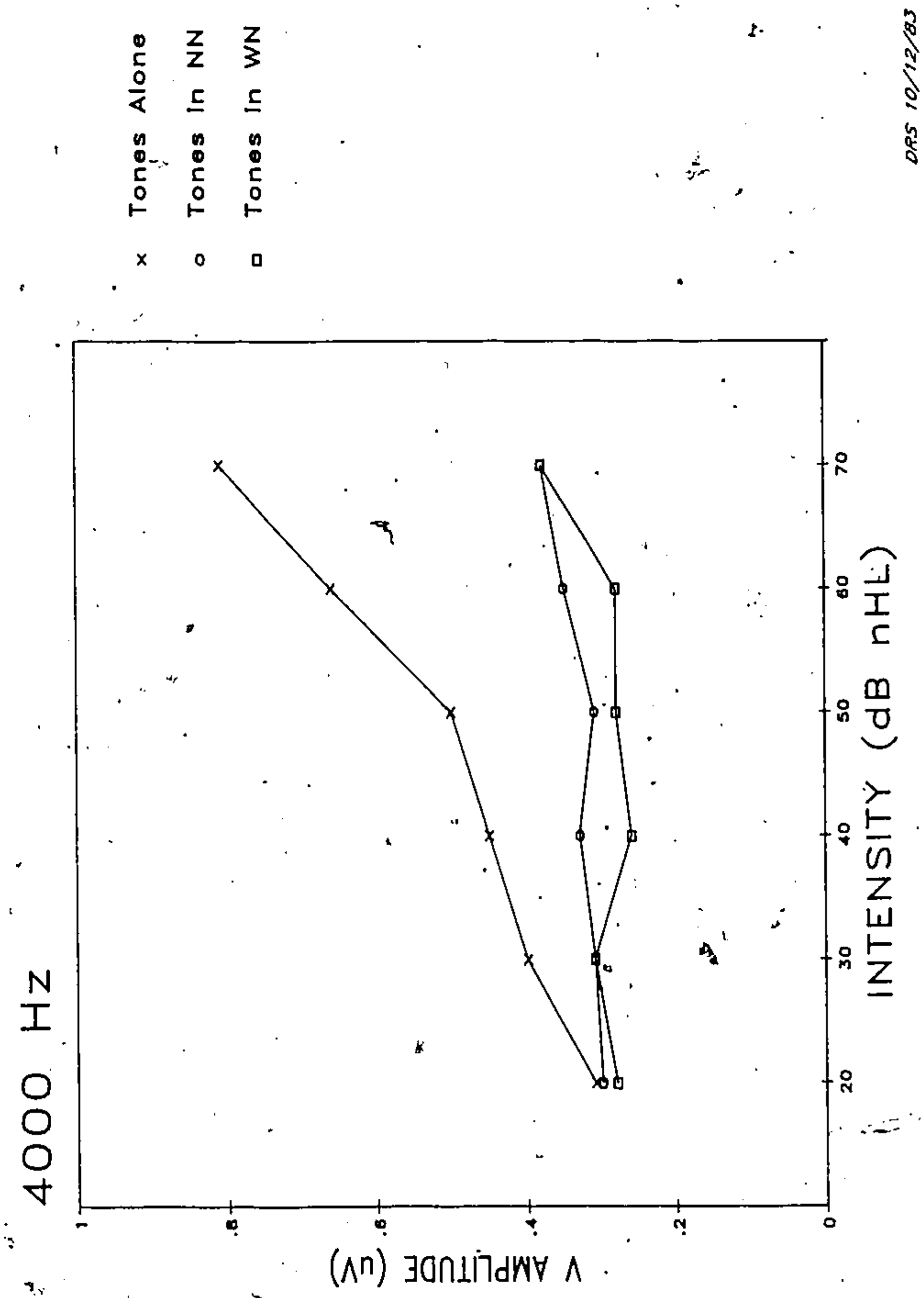
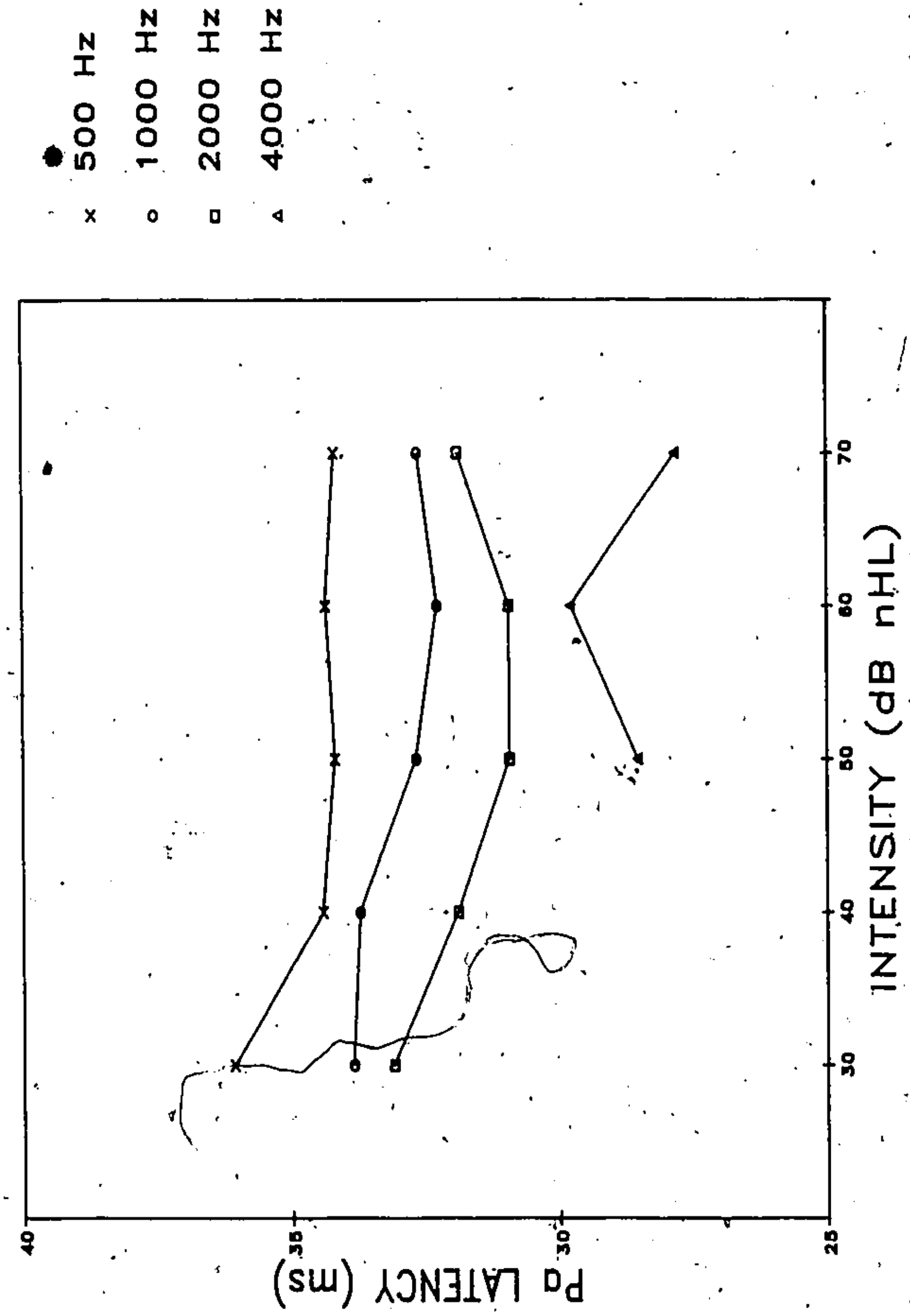
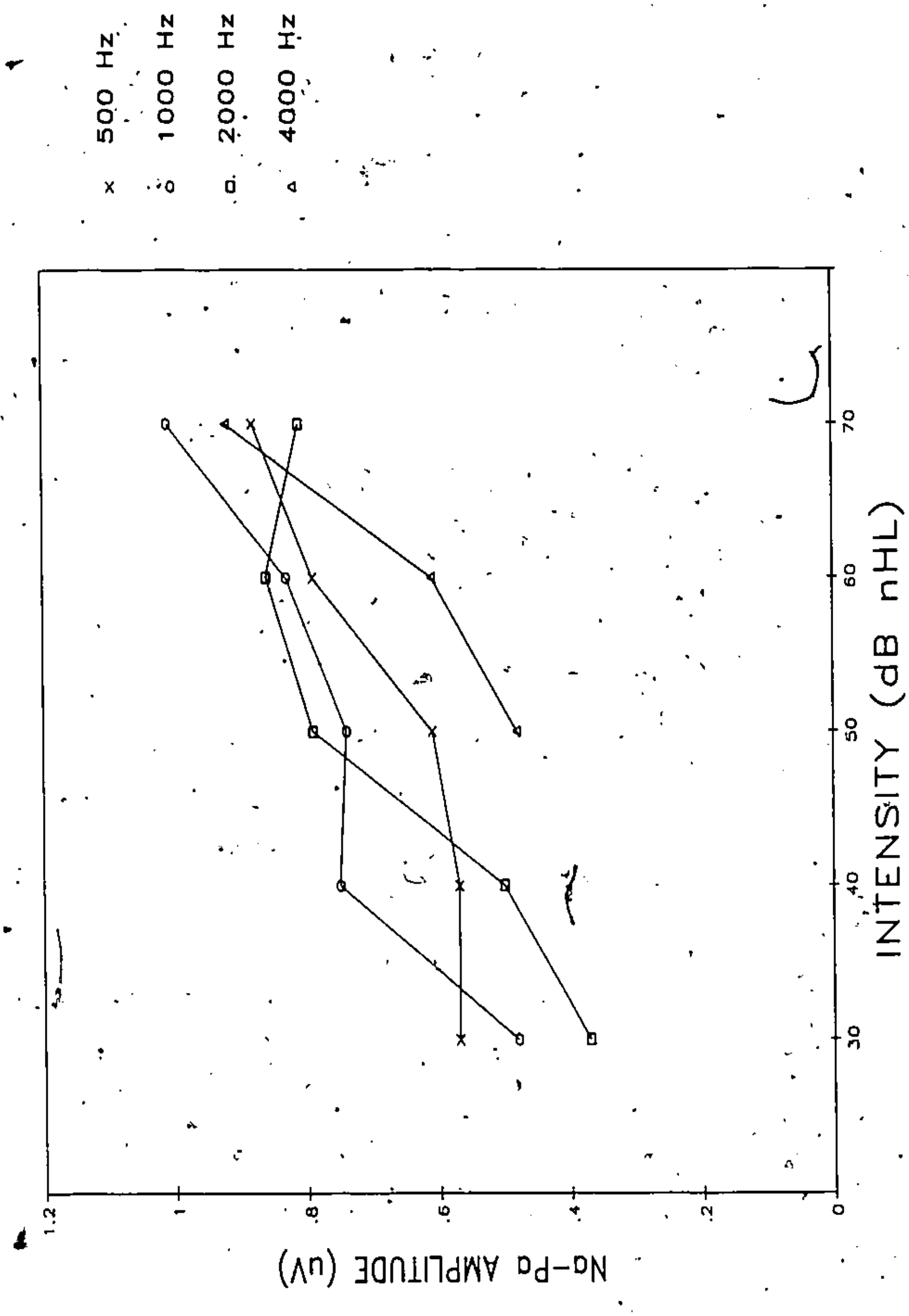

4000 Hz
x Tones Alone
o Tones In NN
□ Tones In WN
DRS 10/12/83
INTENSITY (dB nHL)
20
30
40
50
60
70
V AMPLITUDE (uV)
0
.2
.4
.6
.8
1

Figure 16



DRS 12/10/83

Figure 17



DRS 10/12/83

Figure 18

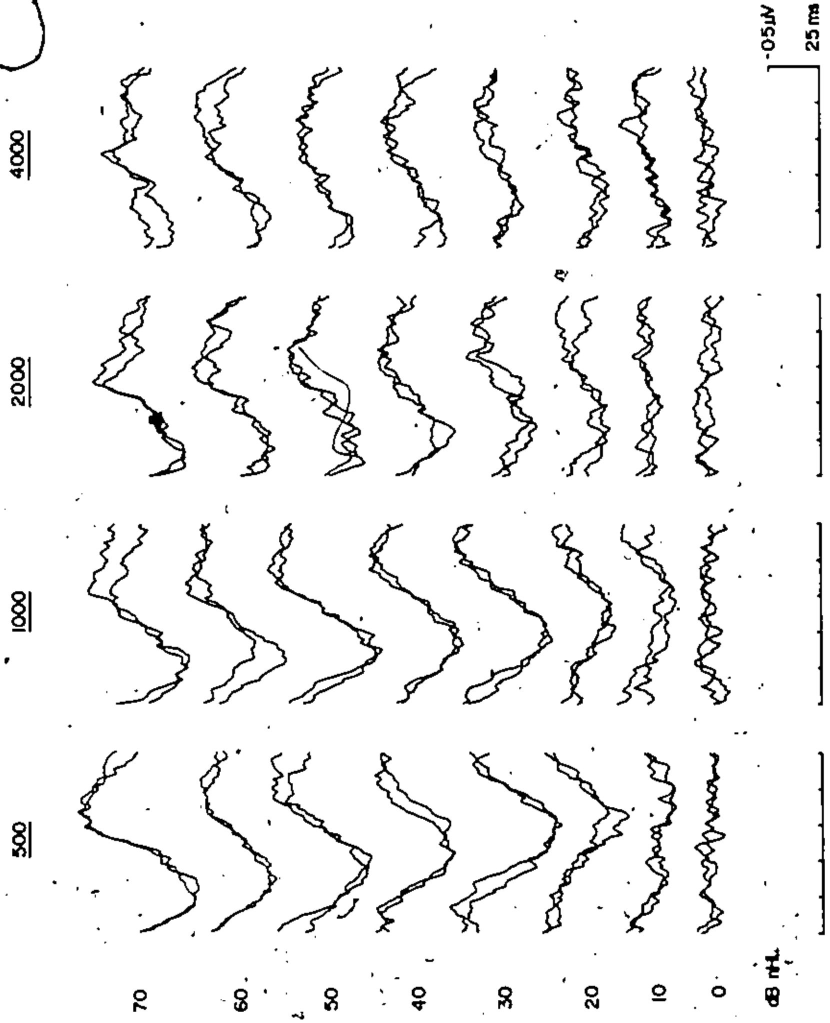
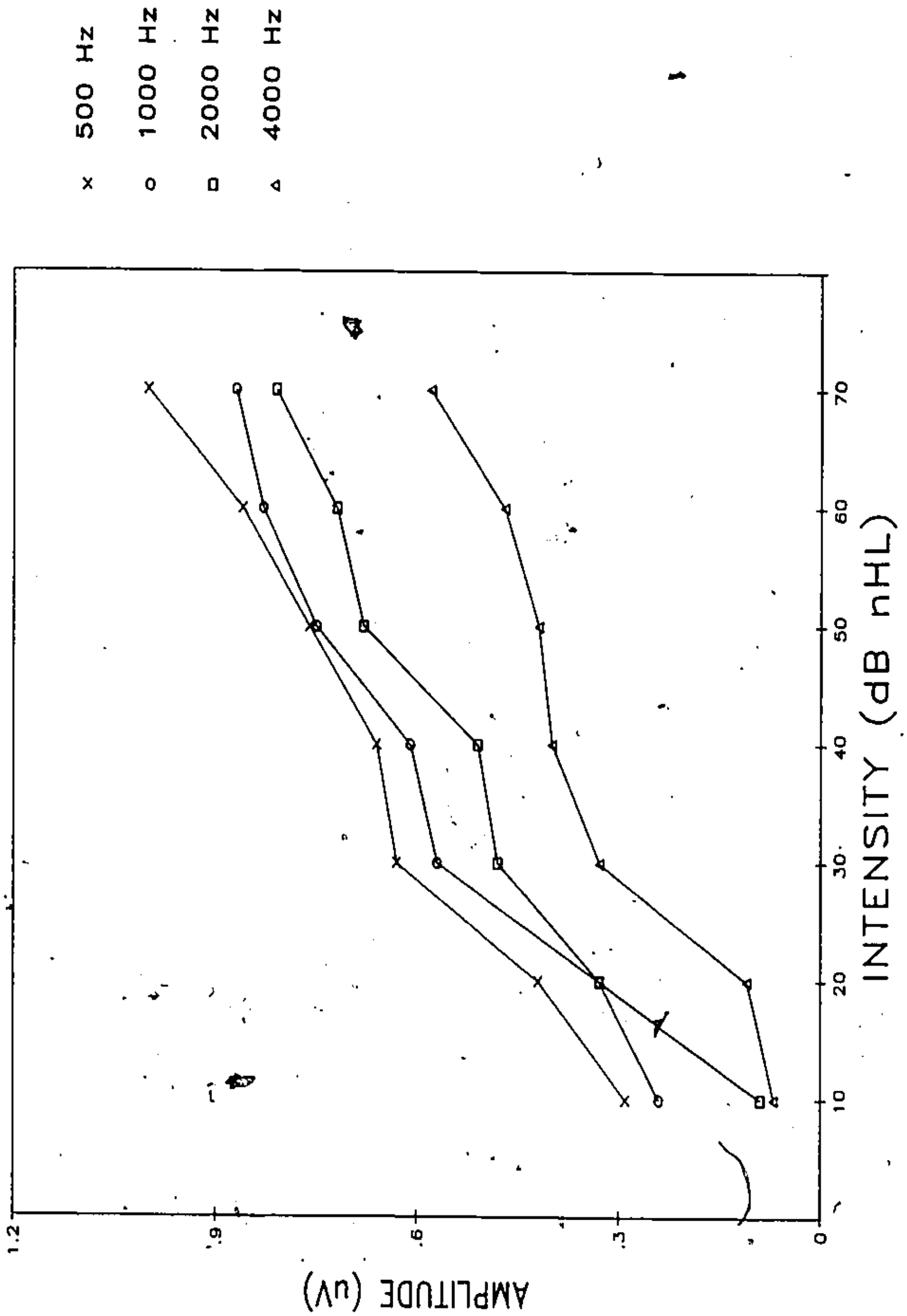


Figure .19



DRS 10/12/83

Figure 20

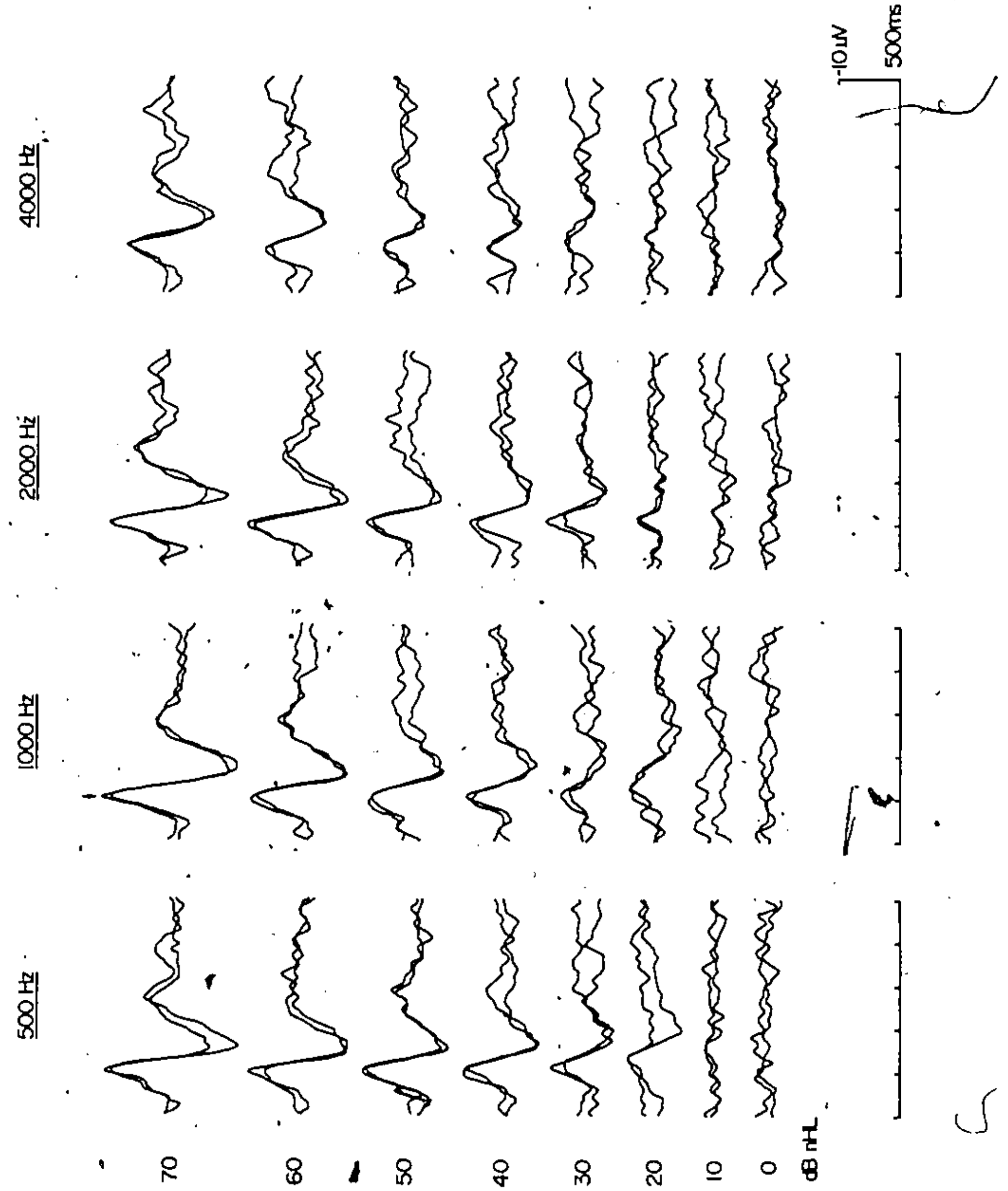
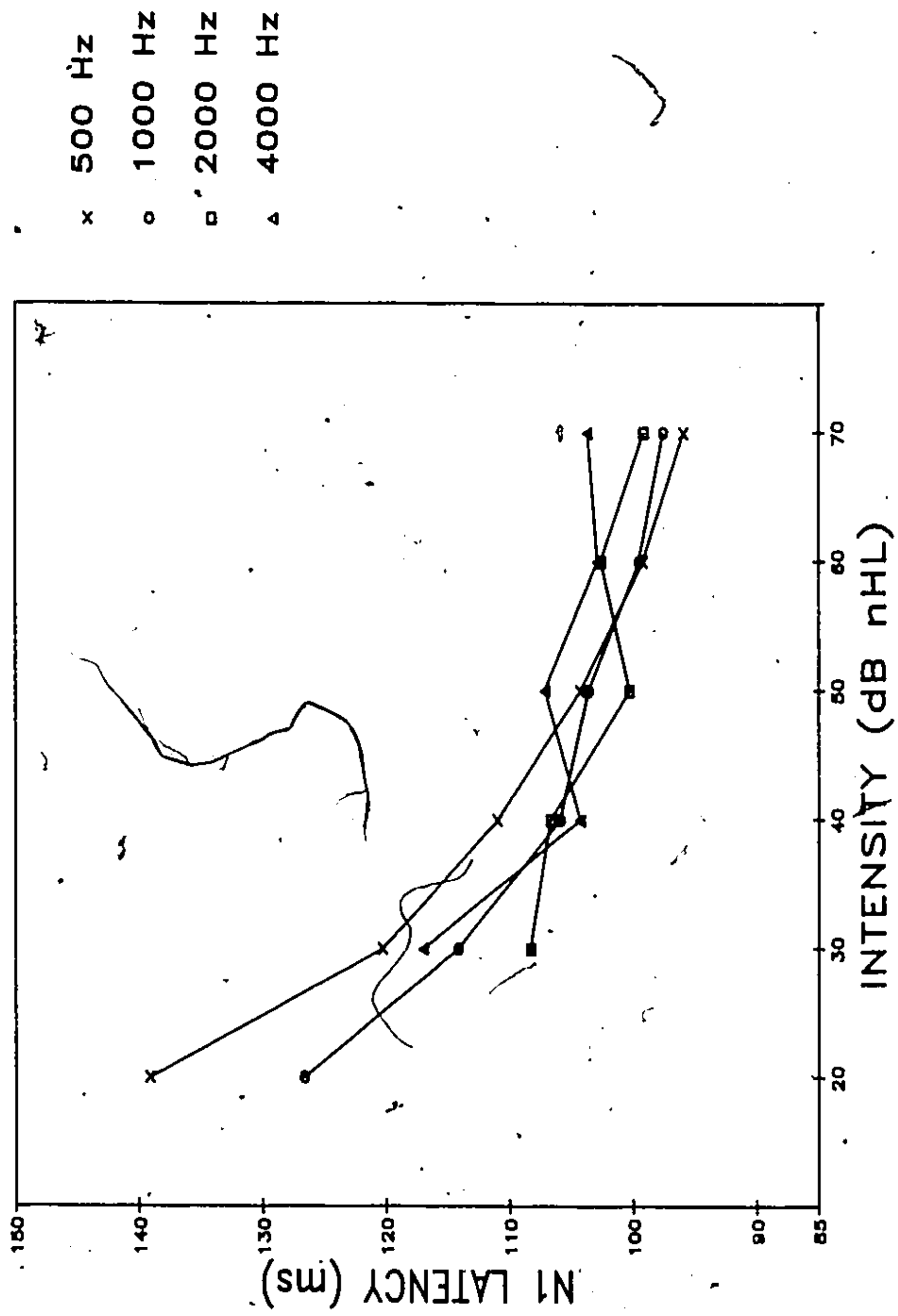
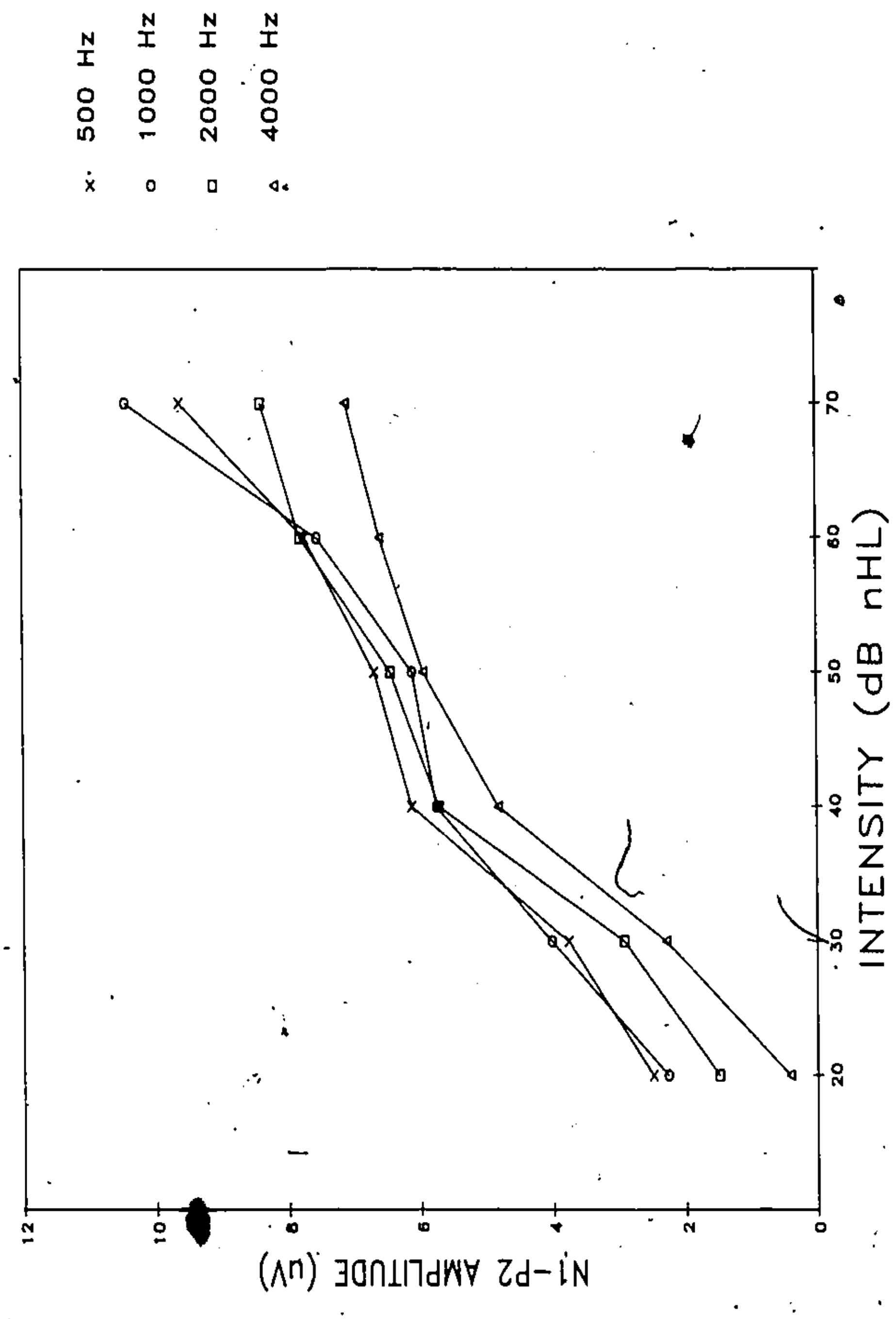

4000 Hz
2000 Hz
1000 Hz
500 Hz
70
60
50
40
30
20
10
0
dB nHL
10 µV
500ms

Figure 21



DRS 13/10/83

Figure 22



DRS 10/12/83

Figure 23

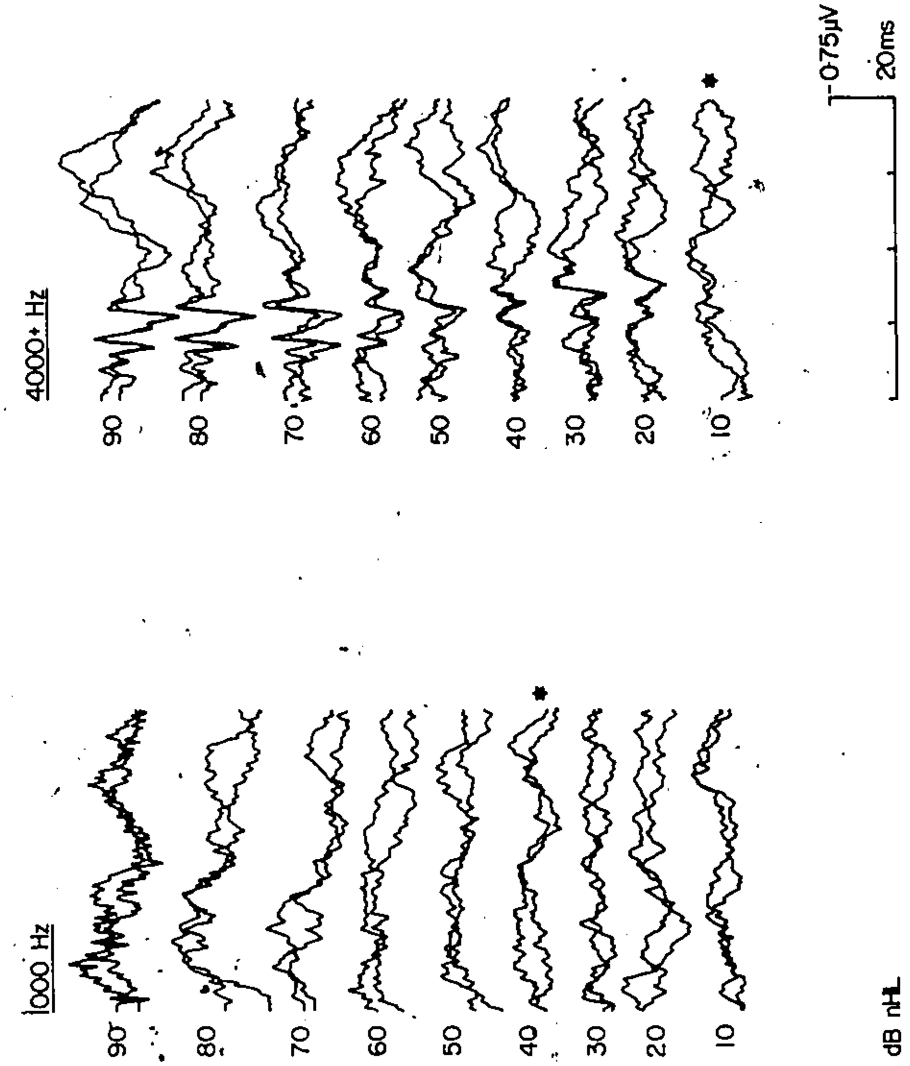

1000 Hz
4000+ Hz
90
80
70
60
50
40
30
20
10
90
80
70
60
50
40
30
20
10
dB nHL
0.75µV
20ms

Figure 24

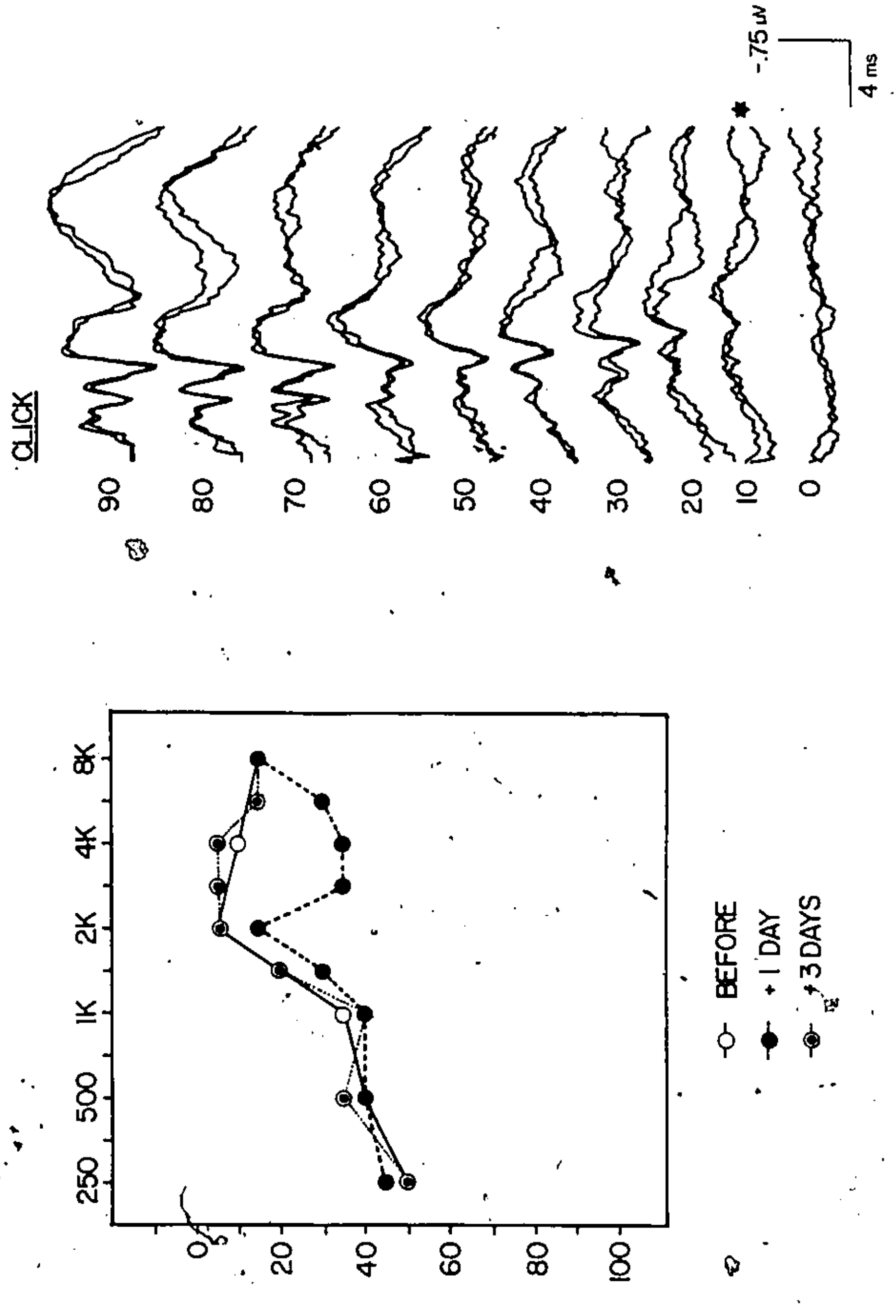

CLICK
90
80
70
60
50
40
30
20
10
0
*
-.75 µV
4 ms
250
500
1K
2K
4K
8K
0
20
40
60
80
100
BEFORE
+ 1 DAY
+ 3 DAYS

Figure 25

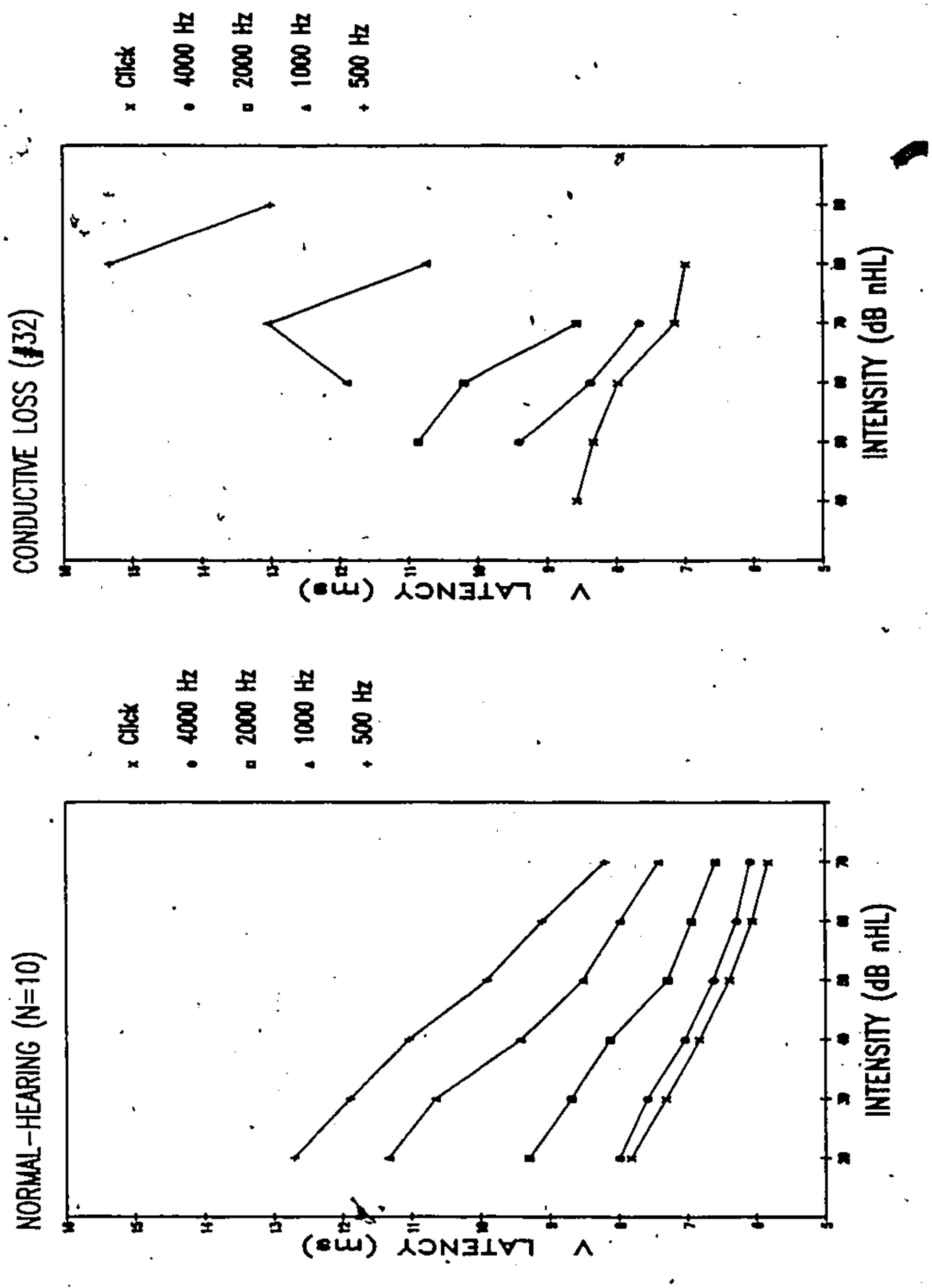

CONDUCTIVE LOSS (#32)
× Click
● 4000 Hz
▫ 2000 Hz
▲ 1000 Hz
+ 500 Hz
V LATENCY (ms)
11
7
INTENSITY (dB nHL)
NORMAL-HEARING (N=10)
× Click
● 4000 Hz
▫ 2000 Hz
▲ 1000 Hz
+ 500 Hz
V LATENCY (ms)
11
7
INTENSITY (dB nHL)

Figure 26

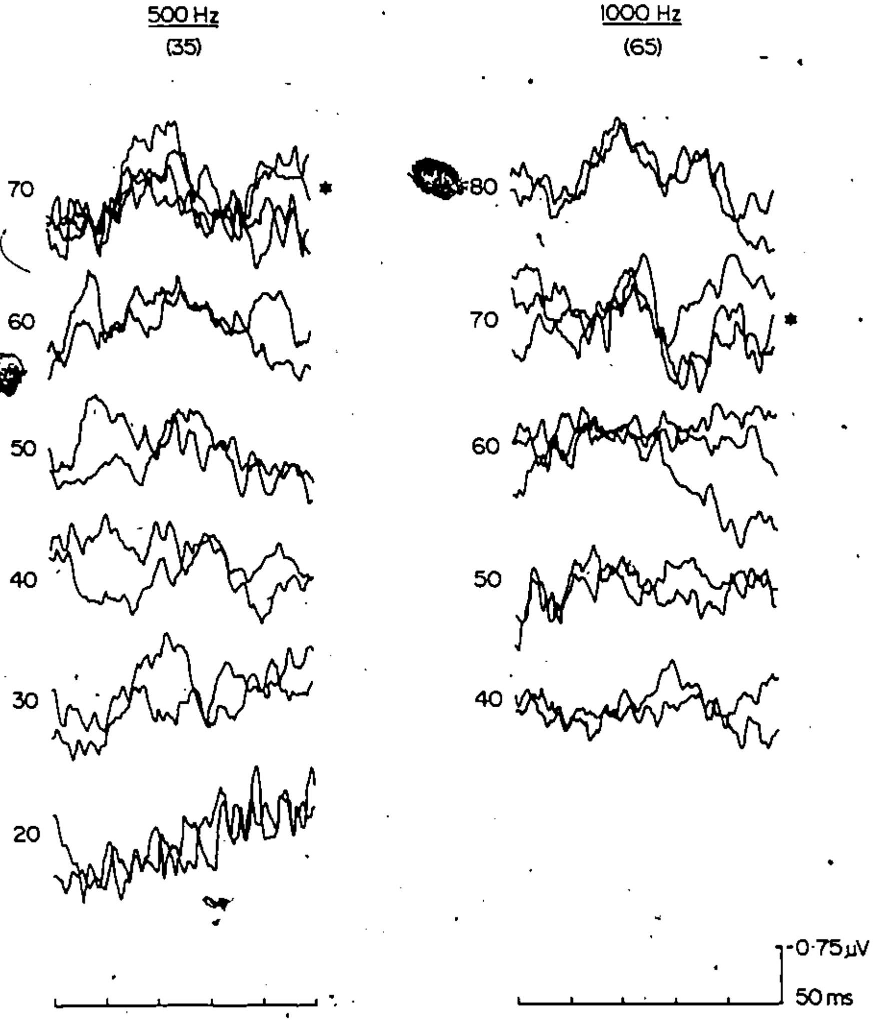


Figure 27

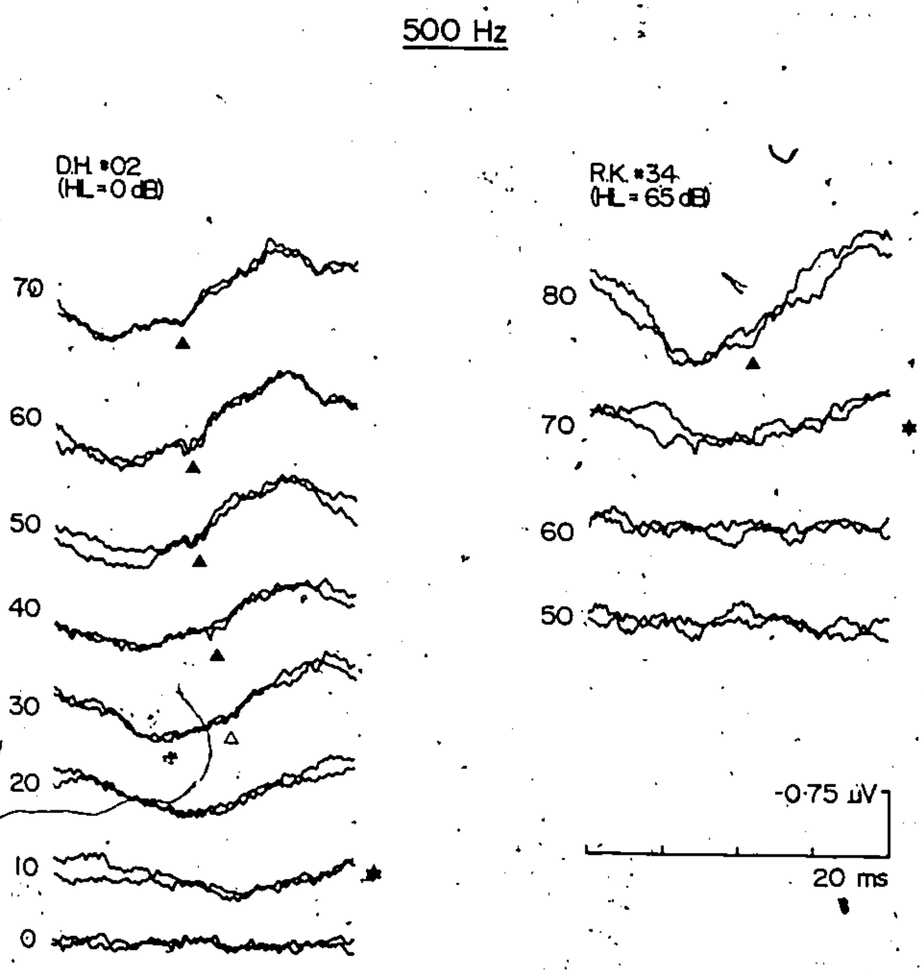

500 Hz
D.H. #02
(HL = 0 dB)
70
60
50
40
30
20
10
0
R.K. #34
(HL = 65 dB)
80
70
60
50
-0.75 µV
20 ms

Figure 28

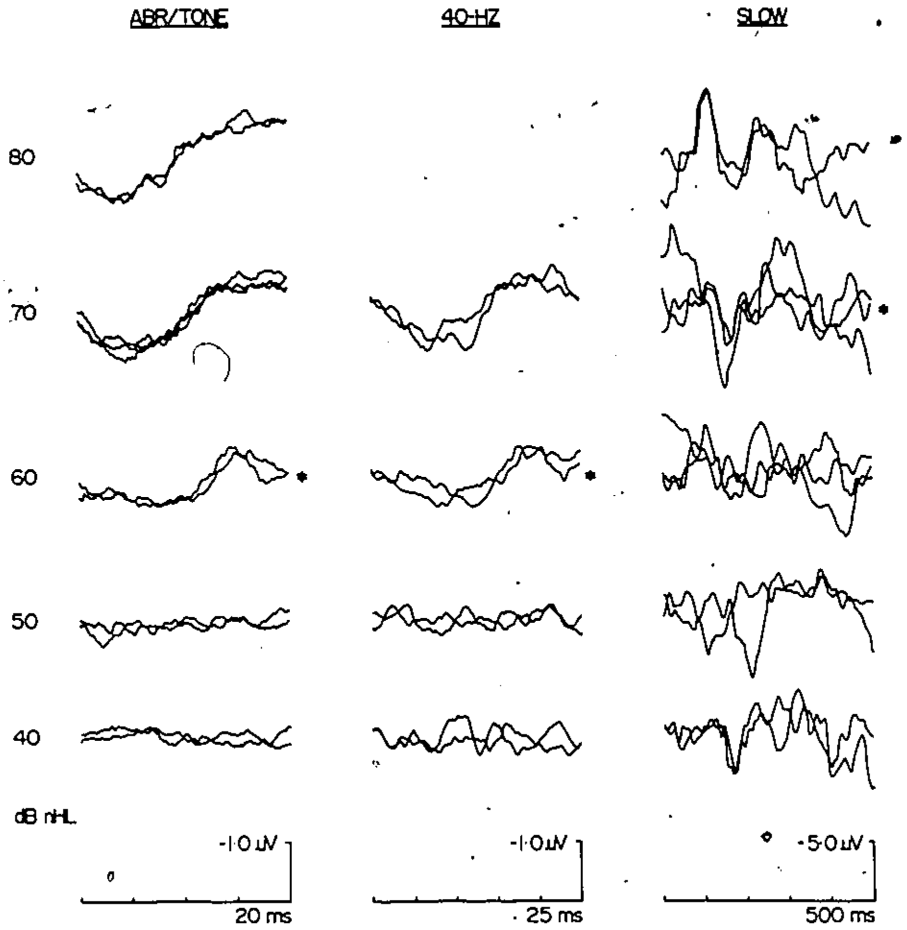

ABR/TONE
40-HZ
SLOW
80
70
60
50
40
dB nHL
-1.0 µV
20 ms
-1.0 µV
25 ms
-5.0 µV
500 ms

Figure 29

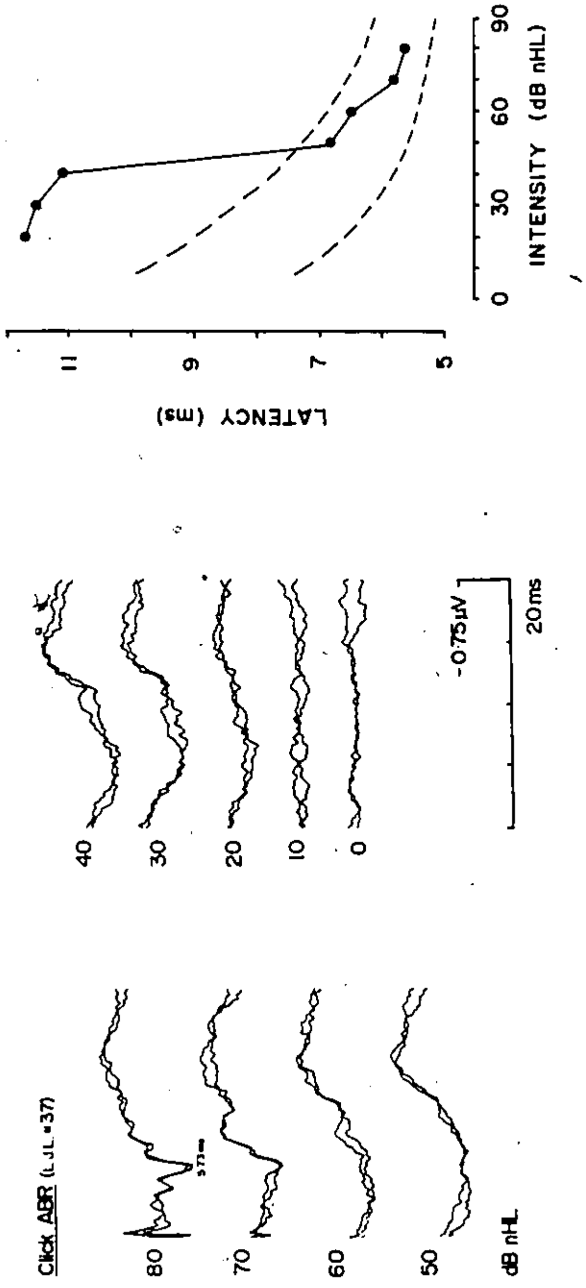

Click ABR (L.J.L. #37)
80
70
60
50
dB nHL
5.72ms
40
30
20
10
0
0.75μV
20ms
LATENCY (ms)
5
7
9
11
INTENSITY (dB nHL)
0
30
60
90

Figure 30

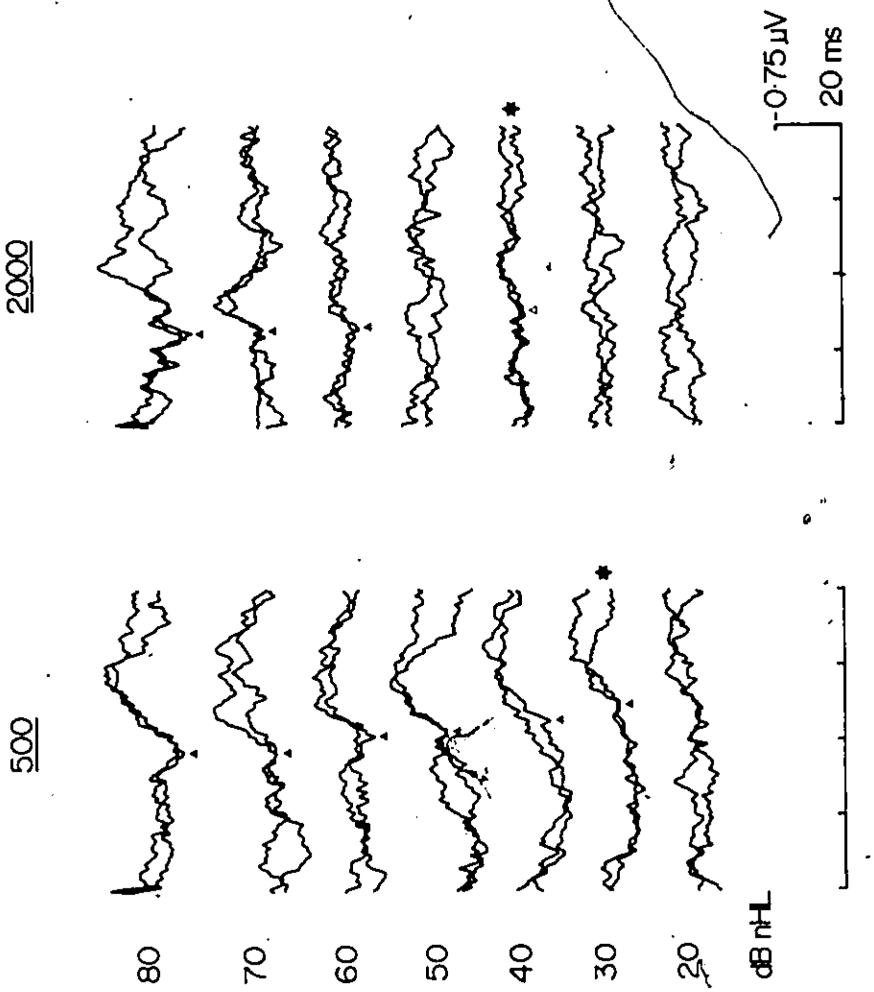


Figure 31

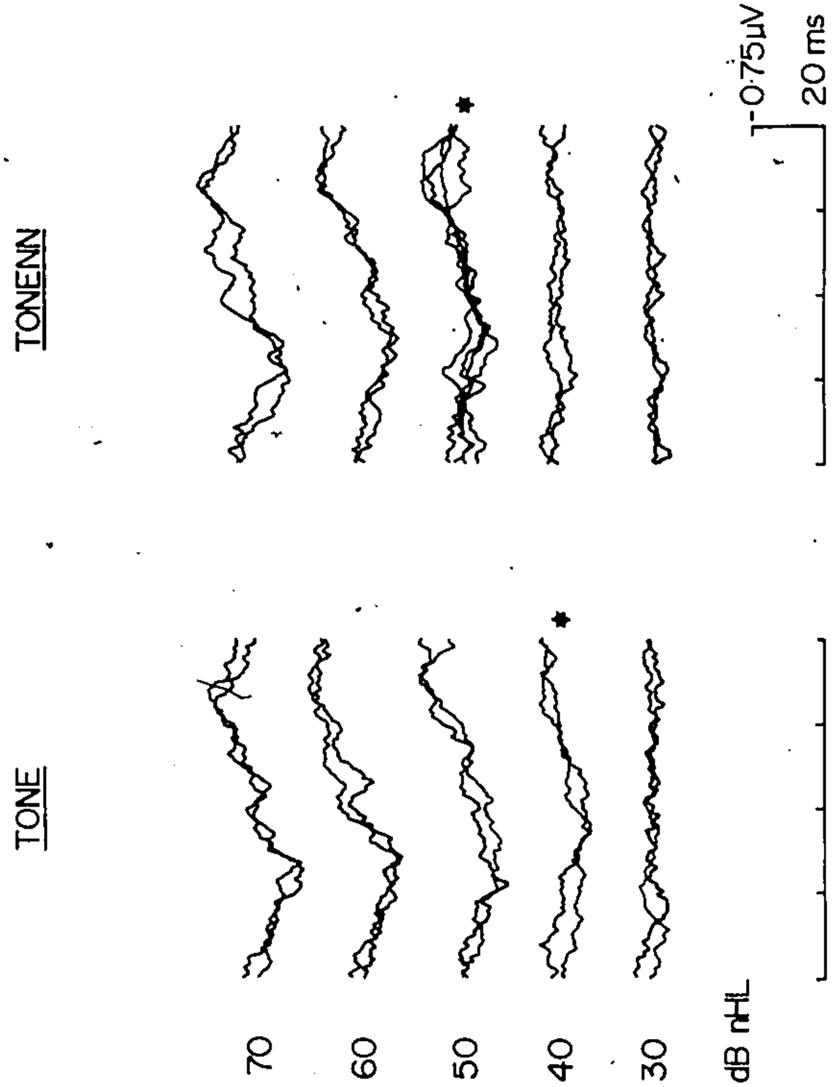


Figure 32

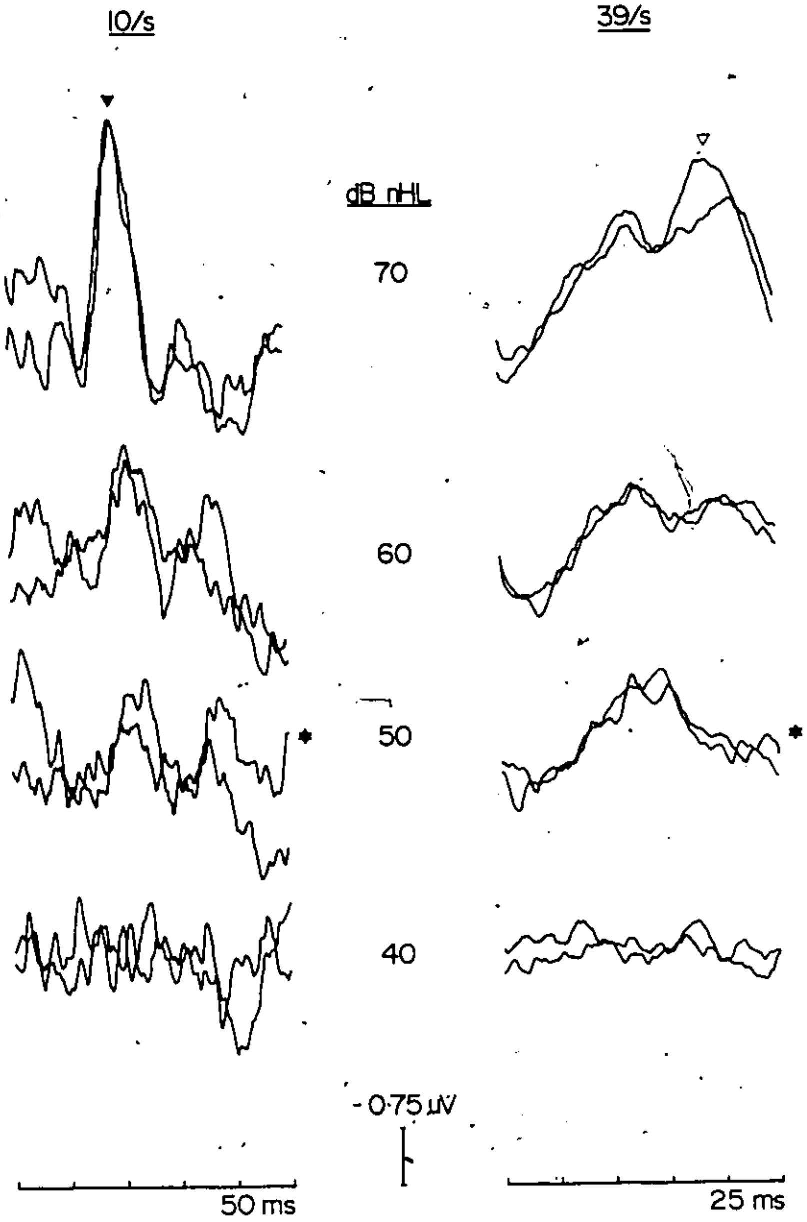


Figure 33

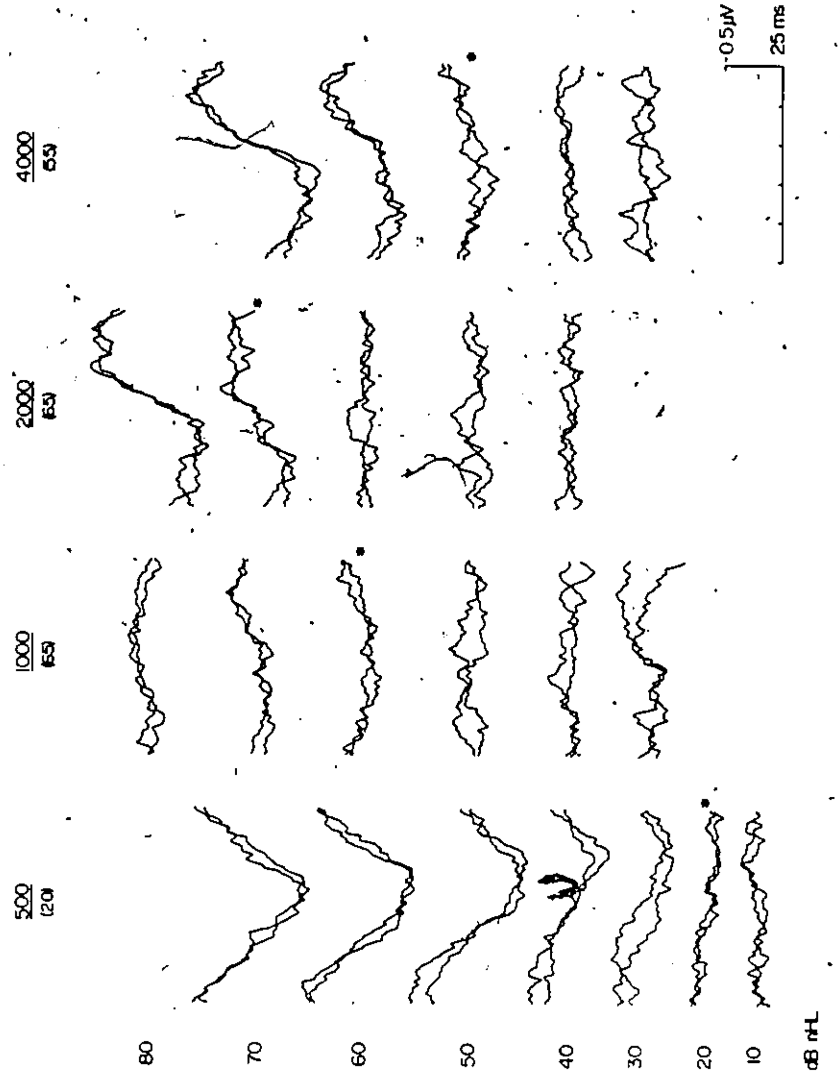

4000
(65)
2000
(65)
1000
(65)
500
(20)
0.5µV
25 ms
80
70
60
50
40
30
20
10
dB nHL

Figure 34

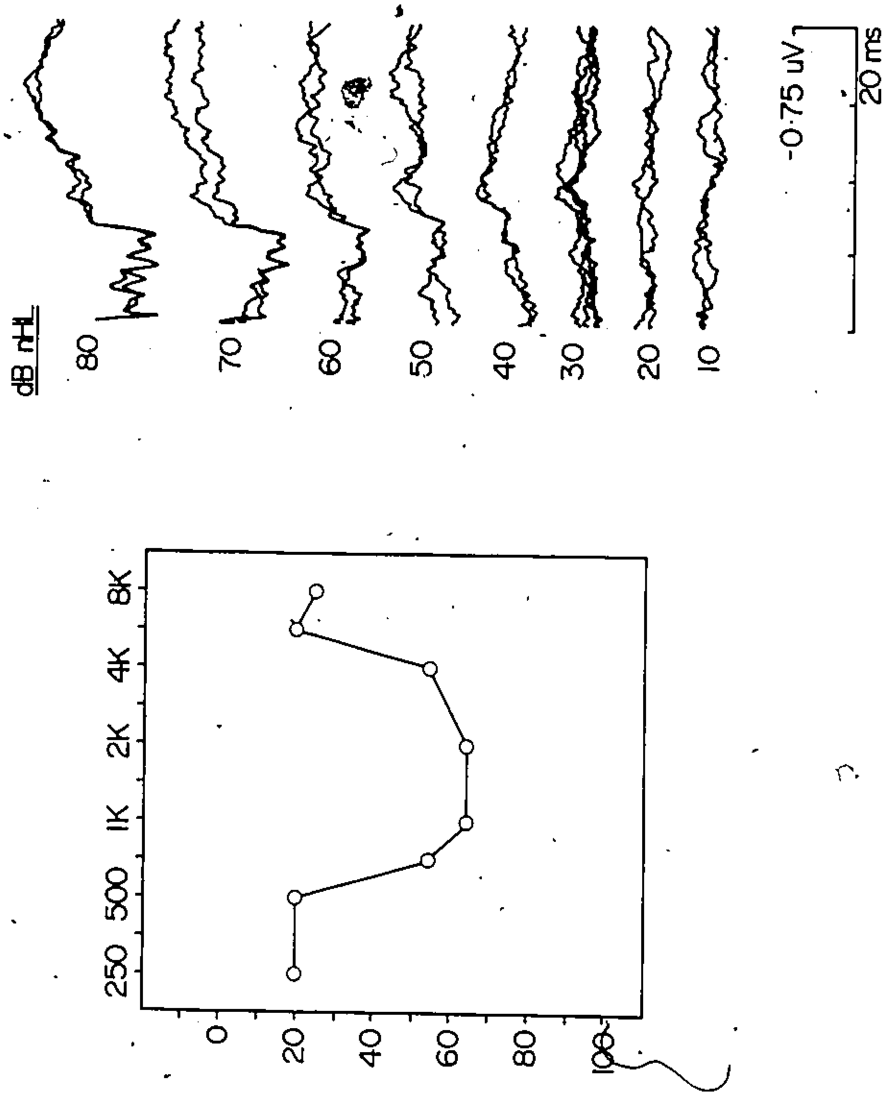

dB nHL
80
70
60
50
40
30
20
10
-0·75 uV
20 ms
250
500
1K
2K
4K
8K
0
20
40
60
80
100

Figure 35

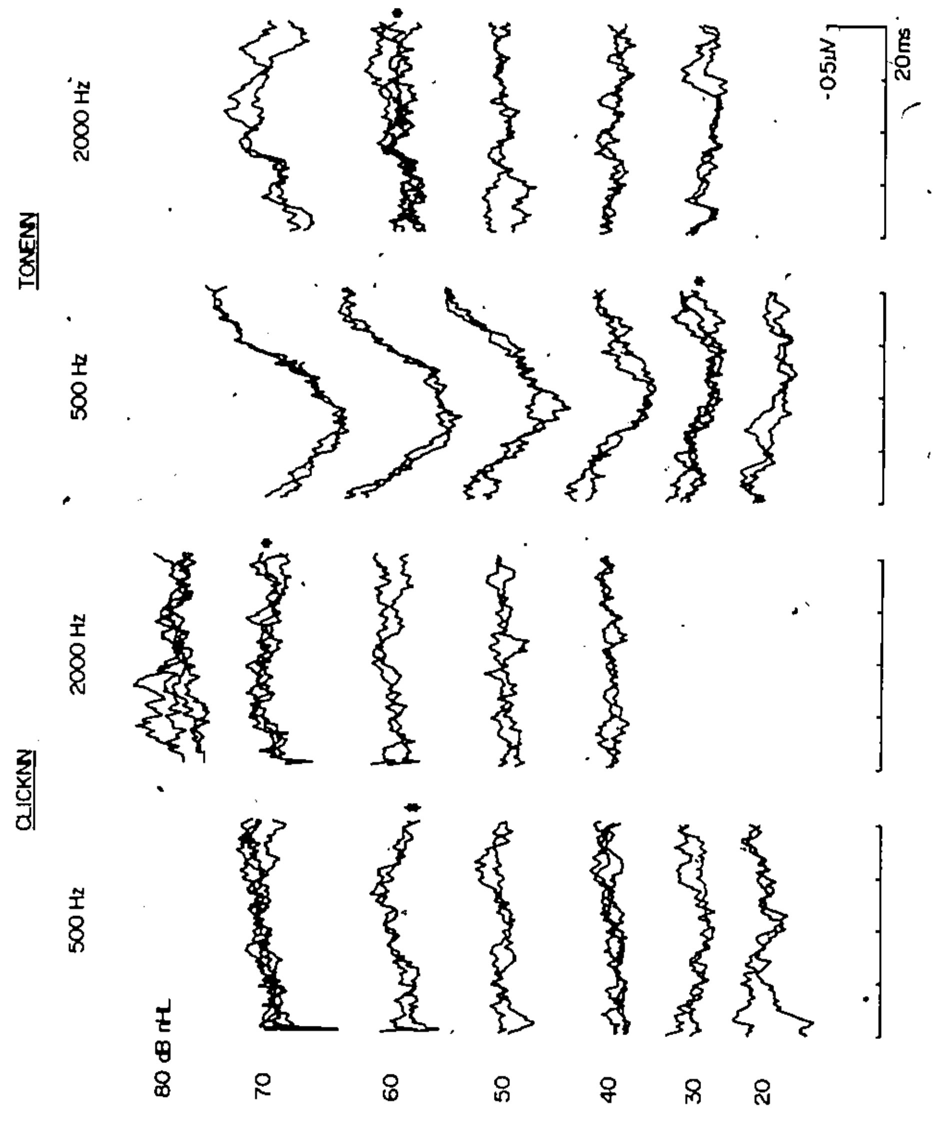

TONENN
CLICKNN
500 Hz
2000 Hz
500 Hz
2000 Hz
80 dB nHL
70
60
50
40
30
20
.05µV
20ms

Figure 36

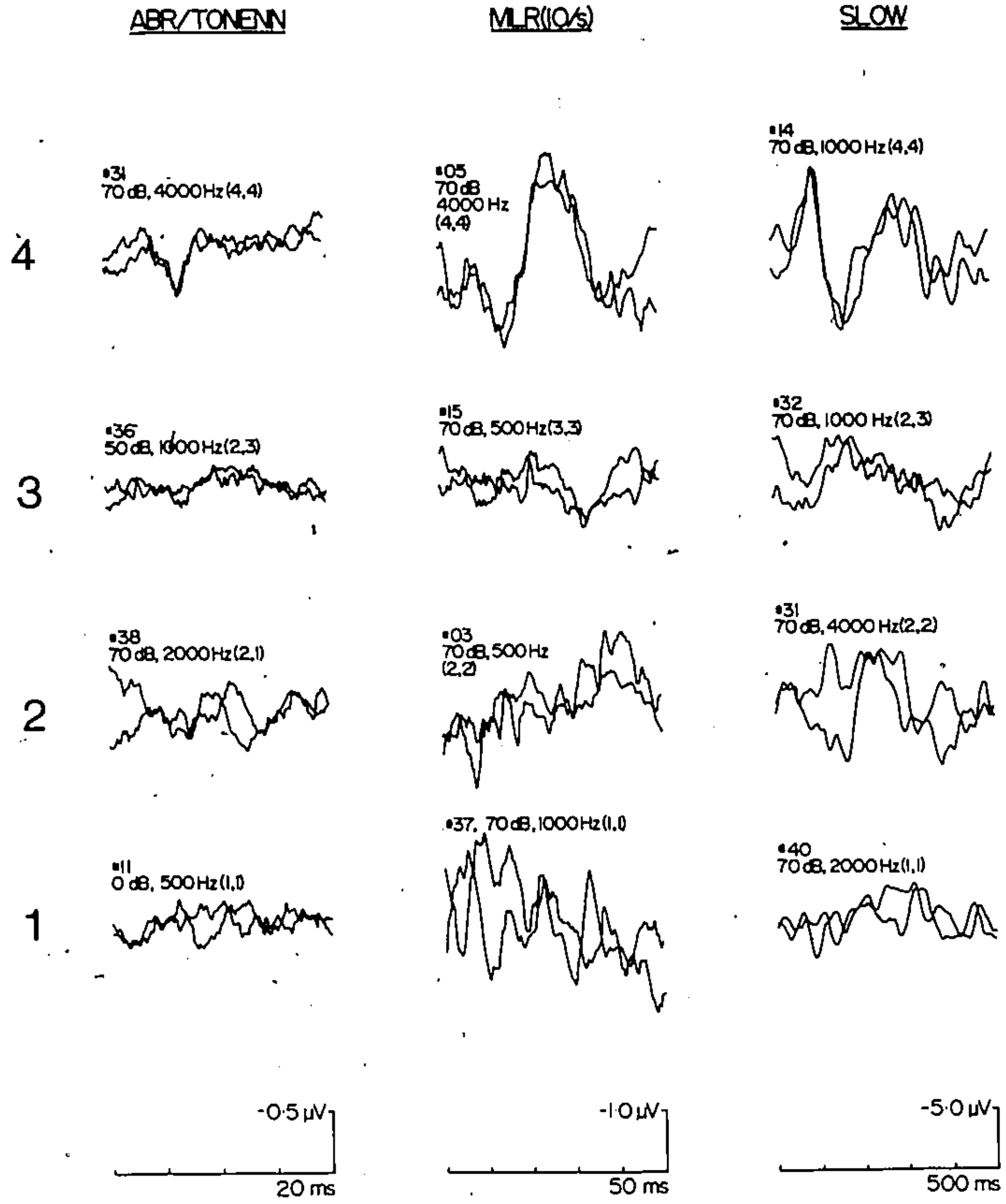
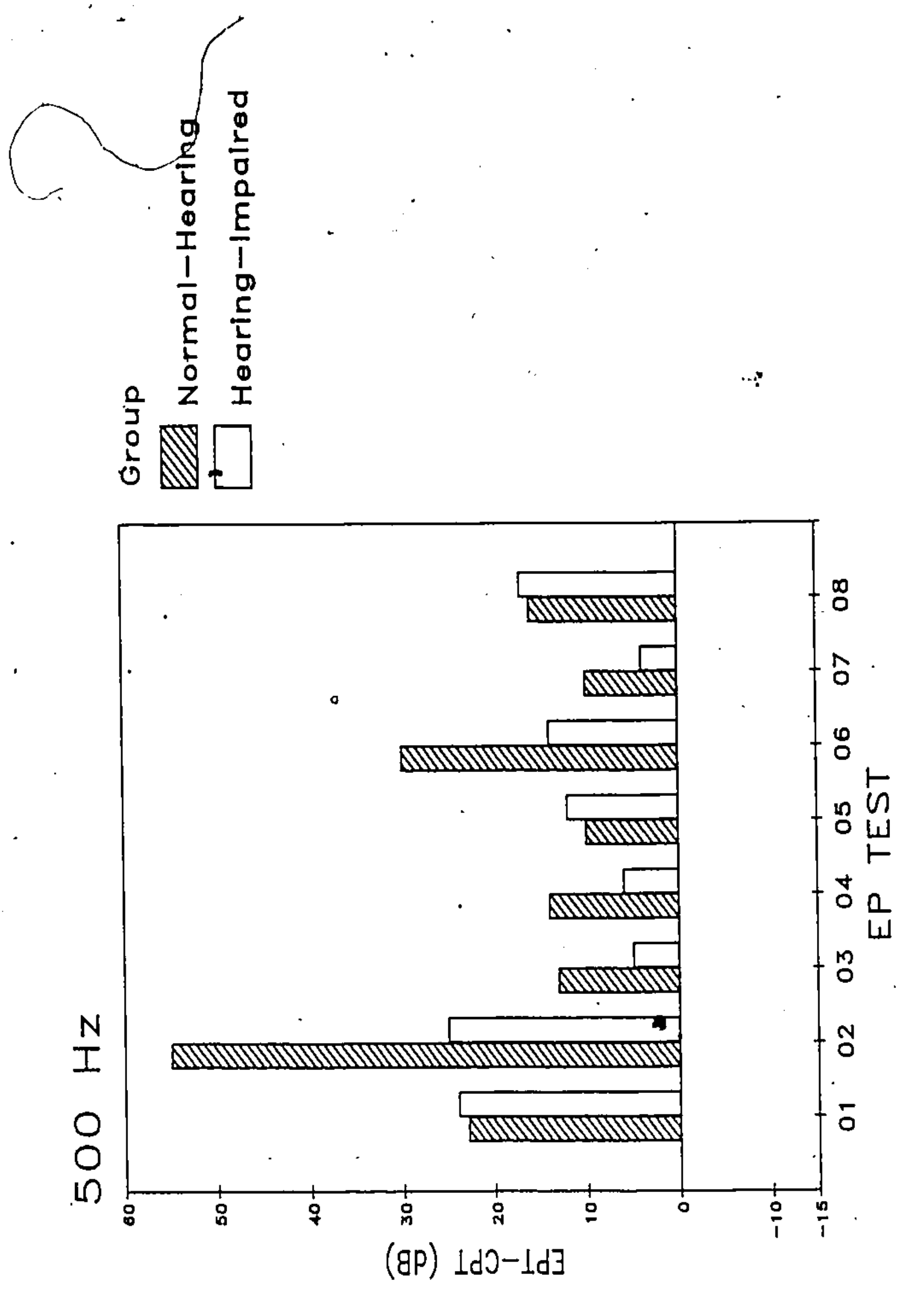
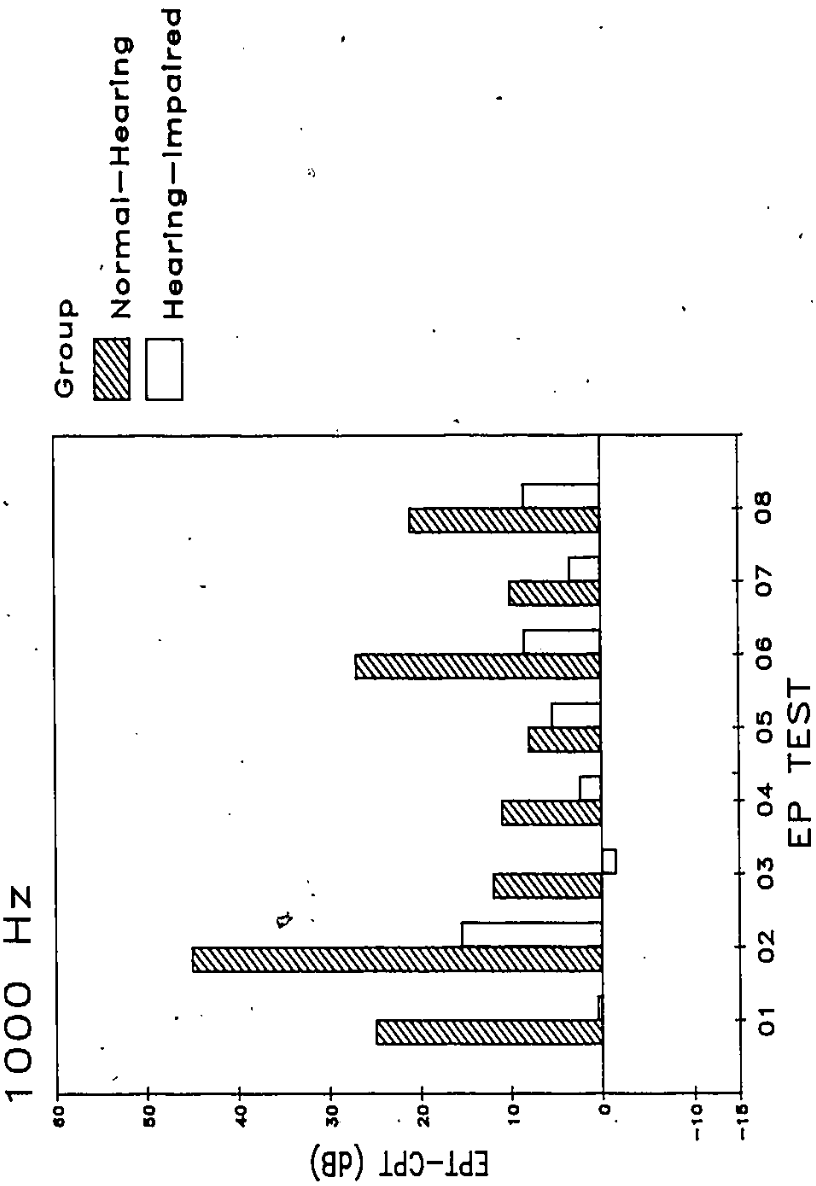

ABR/TONENN
MLR(10/s)
SLOW
4
•31
70 dB, 4000 Hz (4,4)
•05
70 dB
4000 Hz
(4,4)
•14
70 dB, 1000 Hz (4,4)
3
•36
50 dB, 1000 Hz (2,3)
•15
70 dB, 500 Hz (3,3)
•32
70 dB, 1000 Hz (2,3)
2
•38
70 dB, 2000 Hz (2,1)
•03
70 dB, 500 Hz
(2,2)
•31
70 dB, 4000 Hz (2,2)
1
•11
0 dB, 500 Hz (1,1)
•37, 70 dB, 1000 Hz (1,1)
•40
70 dB, 2000 Hz (1,1)
-0·5 µV
20 ms
-1·0 µV
50 ms
-5·0 µV
500 ms

Figure 37



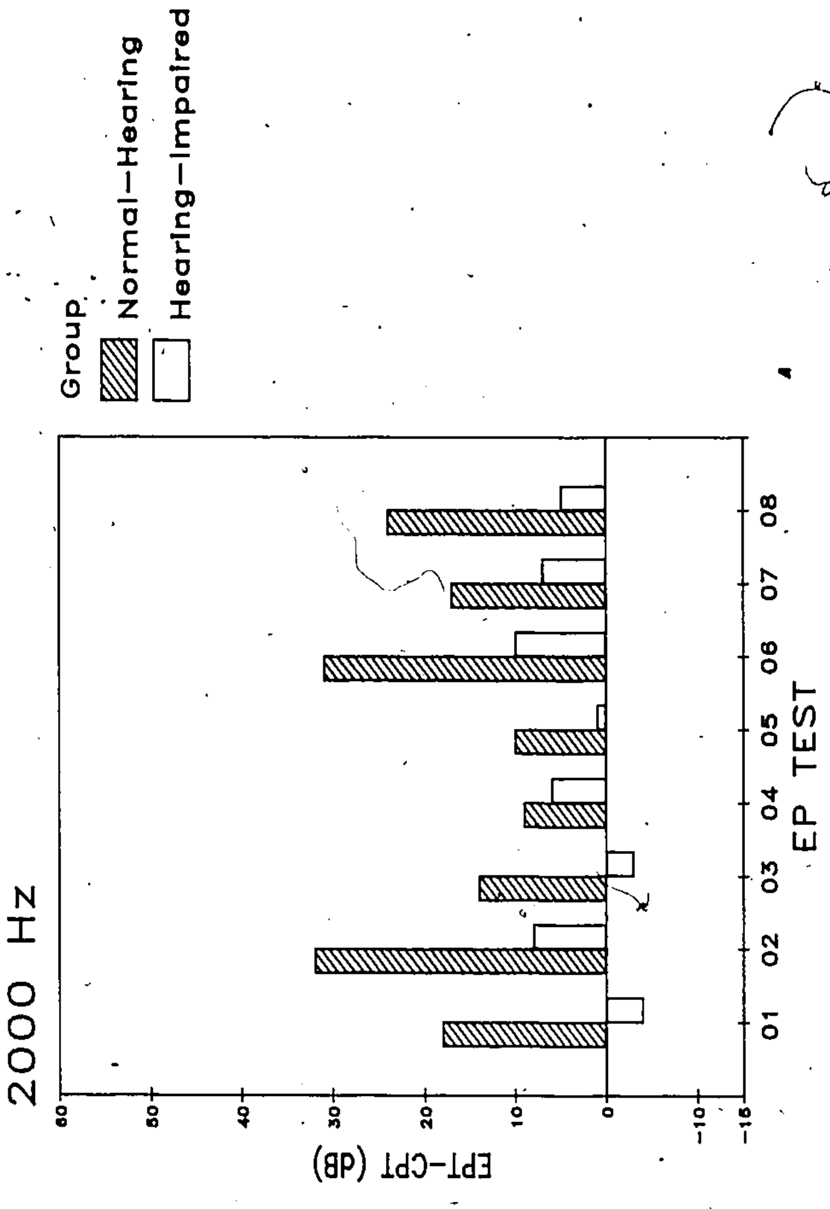
DRS 12/10/83

Figure 38



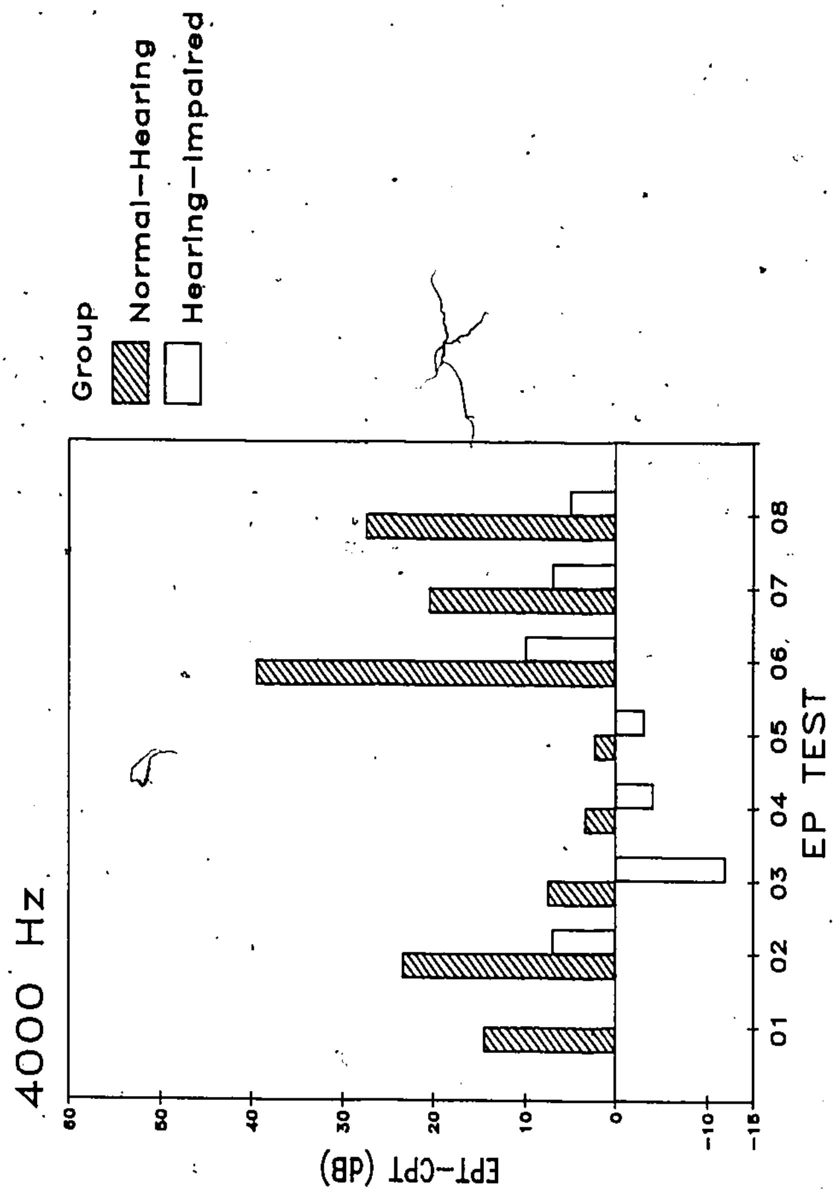
DRS 12/10/83

Figure 39



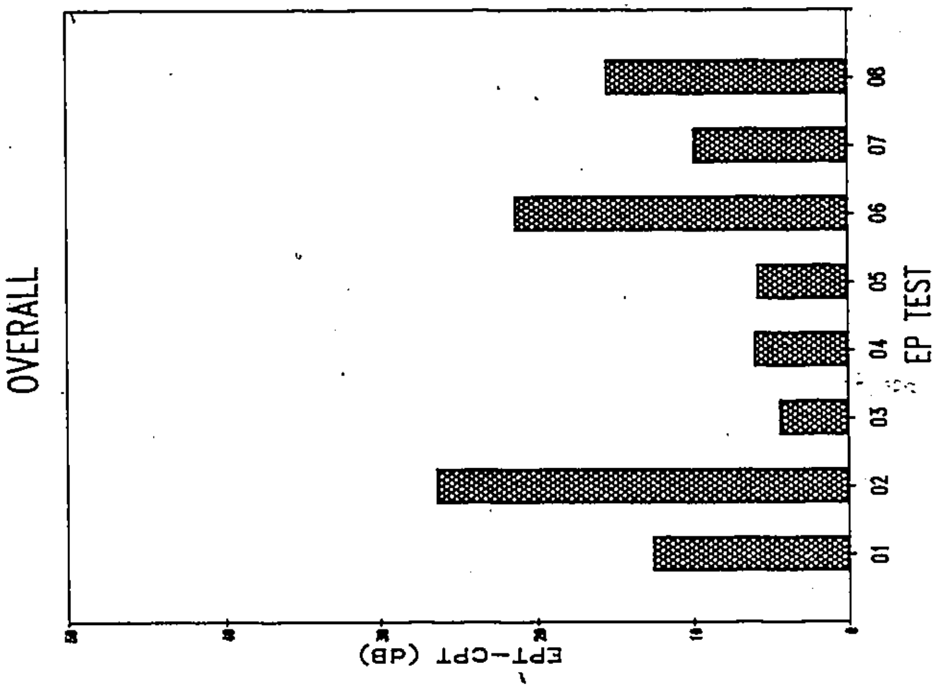
DRS 12/10/83

Figure 40



DRS 12/10/83

Figure 41



DRS 12/14/81

Figure 42

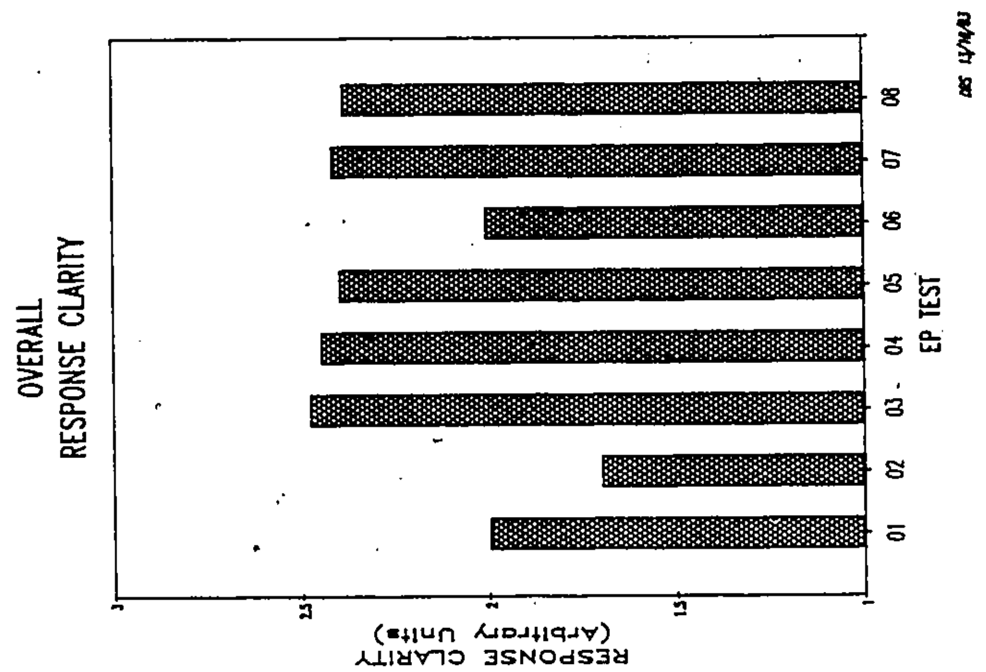
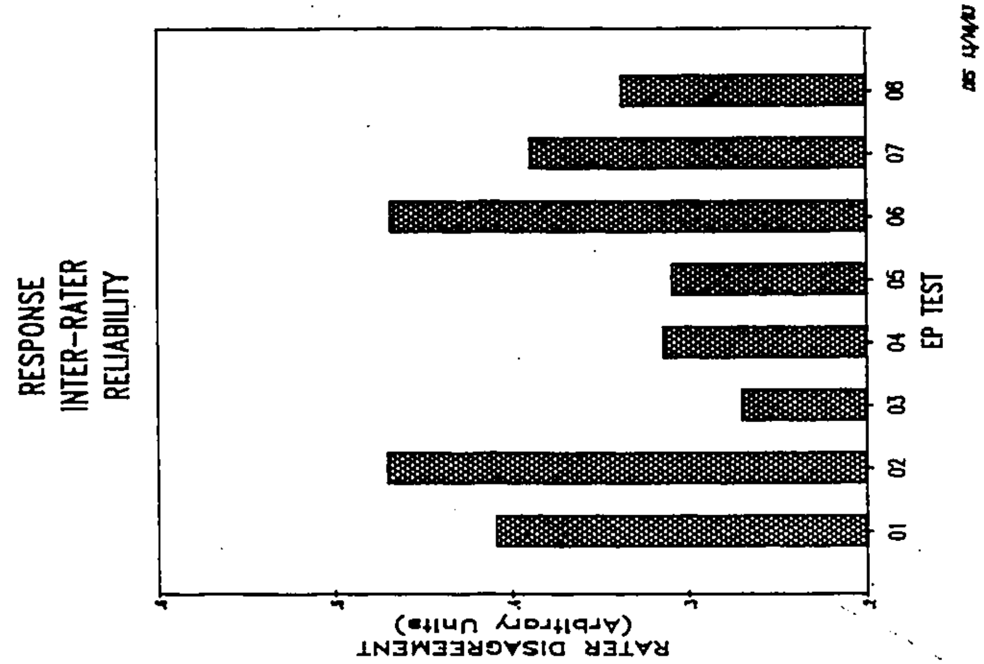

OVERALL
RESPONSE CLARITY
RESPONSE CLARITY
(Arbitrary Units)
3
2.5
2
1.5
1
EP TEST
01
02
03
04
05
06
07
08

Figure 43


RESPONSE
INTER-RATER
RELIABILITY
RATER DISAGREEMENT
(Arbitrary Units)
EP TEST
01
02
03
04
05
06
07
08