This is to certify that the

dissertation entitled

AN INVESTIGATION OF WAVE I' OF THE BRAIN-STEM AUDITORY EVOKED POTENTIAL

presented by

Jacob Japane Mohale Semela

has been accepted towards fulfillment of the requirements for

Ph.D degree in AUDIOLOGY/URBAN AFFAIRS

E. Moore

Major professor

Ernest J. Moore, Ph.D.
Professor

Date 03-04-1992

AN INVESTIGATION Of WAVE I' OF THE BRAIN-STEM AUDITORY EVOKED POTENTIAL

by

Jacob Japane Mohale Semela

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Audiology and Speech Sciences
and
Urban Affairs Programs

1991

ABSTRACT

AN INVESTIGATION OF WAVE I′ OF THE BRAIN-STEM AUDITORY EVOKED POTENTIAL

By

Jacob Japane Mohale Semela

The purpose of this investigation was to determine whether wave I′ in the brain-stem auditory evoked potential (BAEP) was of cochlear or neural origin. Five experiments were performed on 58 female subjects with normal hearing examining the effects of clicks, tonebursts, filter settings, forward-masking, and repetition rates on wave I′.

Experiment I: Thirty-five subjects were tested in this experiment. Click stimuli were presented to the ear at 50, 60, and 70 dB nHL via alternating, rarefaction, and condensation polarities. Wave I′ latency and amplitude were found to be consistent with the input-output functions of the remainder of the BAEP.

Experiment II: Five subjects participated in this experiment. Independent variables used were tone (500, 2,000, and 8,000 Hz), intensity (50, 60, and 70 dB nHL) and phase (i.e., rarefaction and condensation). Wave I′ responses were clearly identifiable at 70 dB nHL for all tone conditions but difficult to observe at lower intensities. As the intensity of the stimulus increased, so did amplitude.

A wider variability was observed for wave I′ than for wave I.

Experiment III: Eight subjects were tested. The experiment showed similar wave I′ patterns to those found in waves I, II, and III of the BAEP. Low pass filter settings yielded clear responses since there was a reduced number of oscillations preceding wave I′.

Experiment IV: Five subjects were tested. Wave I′ latency and amplitude responses were analyzed as a function of delta-T. As delta-T increased to 100 ms, latency of all waves tended to increase. When delta-T was greater than 100 ms, wave latencies grew shorter indicating the tendency to recover. No statistically different F values were found in waves I′ through V for amplitudes and latencies.

Experiment V: This experiment investigated whether repetition rate had any effect on wave I′ and how this potential compared with waves I and III. Five subjects responded to low, middle, and high rates of stimuli. Waveform morphology of responses was studied. Wave I′ rarefaction latency was consistently shorter than those of condensation except at the 10.21 stimuli per second, where the two polarities produced equal latencies. This pattern was observed for waves I and III. On the other hand, condensation produced amplitudes of larger magnitudes than rarefaction for waves I′, I, and III for all three conditions.

The five experiments confirm the view that wave I′ is a neural rather than cochlear potential.

DEDICATION

This achievement is dedicated to my mother, Mmajani, and father, Mohapi who, although expired before I was ten years old, taught me enough to cope with my academics and hardships of life throughout my childhood, adolescence, and adulthood stages. They taught me that with determination, motivation, and steadfastness success is absolutely certain.

It was a Monday morning when my dad woke me up with these words (the last advice he gave me before he passed away), "Young man! wake up and get ready to go to school." These words rang in my mind throughout my scholastic career.

Ke ya leboha, lona ba ha Semela le ba ha Mothopeng. Kgotso! Pula! le Nala Makorong le Mawatleng. Mmupi o le file matla hore le nketse naledi ya meso, lefatsheng la heso le fatsheng la flaga e metsere le dinaledi. Ke Mohale hara Bahale ka baka la lona. Malebo!

ACKNOWLEDGEMENTS

Success of this investigation resulted from collective efforts of sympathetic individuals as well as organizations. Their confidence and trust in me was demonstrated by the helping hand they offered. In expressing my gratitude toward the support system I had during my research endeavors I wish to recognize the following persons: I thank Drs. Deal, Frantz, Mody, Moore, and Smith for having accepted the request to be members of my dissertation committee. By sitting in my committee, they permitted me to draw from their cumulative experience of more than one hundred years. I appreciate the impact Dr. Ernest J. Moore made on me as chairperson of the committee, mentor, and adviser throughout my doctoral studies. I thank Dr. Leo Deal for the extra effort he made in perusing my research material.

My heartfelt thanks are to my nuclear family: Ntete, Kgothatso, Kgotso, and Teboho for having given me the opportunity of delving into doctoral program. Ntete, I recognize the fact that you sacrificed more than a decade on foreign soil so that I may achieve success. I deeply appreciate the understanding that my nuclear family showed while I had to be away from home for long hours seeking knowledge and the fact that we had to live under very tight financial constraints. Malebo Makoro!

I thank and highly appreciate Deborah J. "Mmasetjhaba" Sohn for becoming part of my nuclear family. The fact that Debbie was always available when my family and I needed her, made her not only a friend

in-deed, but part of our family. This earned her the honorable name of Mmasetjhaba--the nation's mother. Malebo! moradi wa Sohn, o entse mosebetsi o kgabileng, ka hoba setho sa lapa laka. Diketso tsa hao ke mohlala o motle le thuto e kgolo ditjhabeng tsa lefatshe. Mme Mma-setjhaba, bana ba thari e ntsho, Afrika Borwa, ba tla thabela mosa wa hao wa ho ba thusa ho tswela pela ho tsa maphelo. Tjheseho ya hao ya ho oka ntsho e kgabile. Ke o lakaletsa katleho le bokamoso bo tjhatsi. Jwaleka setho sa rona, re tla o hopola kamehla.

I thank my research subjects for spending long experimental sessions on my research, for a relatively nominal payment. I express deep appreciation to Randy Robb for the technical assistance he gave me in performing my experiments. I thank Marjorie and Walter Trump who with the aid of Monsanto Chemical Company paid for my research. I appreciate the fact that you walked by my side throughout my studies and witnessed the doctoral degree being conferred on me. I thank the United Nations for paying for my tuition for the 1986-87 academic year, when my financial resources were completely depleted.

Thanks are expressed to our American friends, associates, and fellow christians. For the support they gave us since I landed on American soil. Among these people I find it imperative to give recognition to the following families: Bergs, Blands, Boettchers, Grasmeyers, Sprinkles, and Strokoschs who were always willing to share their income with me when I could not cope with my bills. Ke nnete hore matsoho-mabedi a ya hlatswana. Pula, Kgotso, Nala!

TABLE OF CONTENTS

CHAPTER

II.

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF TABLES

TABLES Page

LIST OF FIGURES

LIST OF FIGURES (Continued)

FIGURES Page

FIGURES Page

FIGURES Page

ABBREVIATIONS

A1	Left earlobe electrode placement
A2	Right earlobe electrode placement
ABR(s)	Auditory Brain-stem Response(s)
A-D	Analog-to-Digital
AN(s)	Auditory Neurophonic(s)
ANN(s)	Auditory Nerve Neurophonic(s)
ANOVA	Analysis of Variance
AP(s)	Auditory Neural Potential
BAEP	Brain-stem Auditory Evoked Potential
BIT	Brain-stem Transmission Time
CAP	Compound Action Potential
CM(s)	Cochlear Microphonic(s)
CNS	Central Nervous System
CPA	Cerebellar Pontine Angle
Cz	Central scalp electrode placement, or vertex electrode placement
D-A	Digital-to-Analog
ECochG	Electrocochleography
EEG	Electroencephalography
EMG	Electromyography
EPSP	Extatory Postsynaptic Potential
FFR(s)	Frequency Following Response(s)
Fpz	Central forehead electrode placement
GPIB	General Purpose Interface Bus
Hz	Hertz (i.e., cycles per second)
IC	Inferior Colliculus

IHC(s) Inner Hair Cell(s)

IPL(s) Inter-peak Latencies

IPSP(s) Inhibitory Postsynaptic Potential(s)

ISI Interstimulus Interval

IWI Interwave Interval

LL Lateral Lemnicus

MI^2 Modular Instrument Incorporation

nano- $1x10^{-9}$ expressed in scientific notation

nHL normal Hearing Level

OAE Oto-Acoustic Emissions

OHC(s) Outer Hair Cell(s)

pe SPL Peak Equivalent Sound Pressure Level

PE SPL Peak Equivalent Sound Pressure Level

PTC(s) Psychophysical Tuning Curve(s)

SA Signal Averaging

SP(s) Summating Potential(s)

SP_1 Signal Processing

SPL Sound Pressure Level

SOC Superior Olivary Complex

TTS Temporary Threshold Shift

TTX Tetrodotoxin

CHAPTER I

INTRODUCTION

Modern technology and urbanization have affected human lifestyles in many ways. The impact of modern technology and automation may be summarized in terms of the following changes and developments: (a) modern medical training and public health education; (b) use of machines in urban areas and modern societies (such as those used for domestic purposes, entertainment, transportation, and industry); and (c) extensive use of drug therapy (e.g., treatment with tranquilizers, diuretics, antibiotics, and other chemicals substances) (Paparella & Jung, 1983).

According to Cohn and Koushki (1991), during the last twenty to thirty years noise has grown to be a pervasive factor in urban life. Transportation noise continues to be one of the most pervasive and hard-to-control sources of modern and developing cities. Consequently, there is increasing concern among urban communities about the effects of exposure to loud and continuous noise over a long duration.

As a result of medical technology and public education on health care, the overall life span of the human race has increased. This is evidenced by the quality of life often found in urban cities, particularly among affluent suburban residents (as compared to most inner city residents). Although the life span has increased with modern medical technology, there is neither medical nor surgical treatment for age-related hearing impairment (or presbycusis). Consequently, the present demographics reveal that there is a higher incidence of sensorineural hearing loss now than was found in the

pre-industrialization era.

Unfortunately, urbanization cannot be separated from modern machinery and automation. As a rule, machines cannot operate without producing noise; consequently, individuals living in most industrialized countries throughout the world are constantly exposed to excessive amounts of noise (i.e., unwanted sound in various forms). For example, individuals are exposed to noise produced by household equipment such as washing machines, dishwashers, and dryers; leisure machines such as snowmobiles, and musical instruments; modes of transportation such as automobiles, trains, and aircraft; and at the work place where industrial noise such as that emitted by sledgehammers is prevalent. Thus, through the operation of machines in urban areas, a man-made disease has been created in the form of a noise-induced hearing impairment.

Modern medical treatment involves mainly the use of drugs, and most drugs have side-effects. In addition, drug therapy is usually administered to all population age-groups. For example, a significant number of the geriatric population require drug treatment for monitoring their age-related physiological malfunctions, such as hypertension, calcium deficiency, arthritis, arteriosclerosis, liver and pancreas disorders—as seen in diabetes. Common medication for these disorders are antibiotics, diuretics, and other drugs of the aminoglycoside family.

The economically disadvantaged urban populations commonly have a high incidence of respiratory diseases such as tuberculosis. Most of these patients are treated with ototoxic drugs such as streptomycin, gentamycin, and tobramycin. Inherent within the economically

disadvantaged populations are teenage mothers which, in addition to a low level of literacy, result in at-risk infants. This pediatric population often has a high incidence of children who need intensive care and thus, are commonly exposed to continuous incubator noise for long periods during their stay in the hospital. In most cases these children are also treated with antibiotics.

Common to the three types of urban-related sensorineural hearing losses identified previously (prebycusis, noise-induced hearing loss and drug-induced hearing impairment) are the following distinctive features: (a) they begin by damaging the inner ear; (b) the basal part of the cochlea is first affected and (c) individuals often complain of bilateral tinnitus (commonly, described as ringing, hissing, or roaring in the ears). These anomalies are usually detected through anatomical, psychophysical, or electro/physiologic tests. Our emphasis here is on the extensions of electro/physiologic test--the brain-stem auditory potential (BAEP).

While there are several behavioral and electrophysiologic audiologic evaluation procedures that can be used to identify sensorineural hearing loss, most if not all, are inadequate to more precisely determine various anomalies of the auditory nerve. It is within this context that a relatively new wave and electro-physiologic technique is proposed so as to more clearly delineate various pathologic conditions that may occur at the level of the auditory nerve--the wave I' potential of the BAEP.

Purpose of the Investigation

It is the purpose of this study to investigate the effects of event-related acoustic stimulus parameters on the excitatory postsynaptic potential (EPSP or "EPSP-like") of the compound action potential (CAP) of the eighth cranial nerve. This investigation examines if the wave that precedes wave I, wave I′, of the BAEP and electrocochleographics responses (ECochG), is a neural or cochlear potential. To achieve this goal, the CAP responses are analyzed as dependent variables of stimulus intensities, repetition rates, and delta-t within the forward masking paradigms. Since wave I′ is very small in relation to the remainder of the BAEP wave amplitudes, emphasis of the present study is placed on the suprathreshold intensity levels within several ECochG parameters. In this manner, a 5.0 ms analysis time will be used thus producing the CAP responses with higher resolution than with the BAEP regular analysis time of 10 ms.

In addition, this investigation seeks to determine if the wave I′ behaves differently from wave I in response to various acoustic parameters. Stimulus parameters employed as independent variables in the investigation are bandpass settings, click polarities, repetition rates, as well as intensity. Bandpass filter settings used were 10-10,000 Hz, 10-5,000 Hz, 100-3,000 Hz, and 300-3,000 Hz. All three aspects of stimulus polarity, such as alternating, rarefaction and condensation were nested within each bandpass. Three stimulus repetition rates were selected which consisted of 3.22 pulses/sec,

10.21 pulses/sec, and 96 pulses/sec. The intensity series were 70, 60, and 50 dB nHL.

Null-Hypothesis:

(1) Wave I' is a non-neural potential which precedes wave I of the BAEP;

(2) Wave I' of the BAEP is a transient summating direct current of cochlear potential

Hypotheses:

Wave I' of the BAEP is a neural potential in the cochlea

Significance of the Investigation

Since the application of the far-field technique for recording evoked "cochlear-action potentials" from human scalp (Sohmer & Feinmesser, 1967) and identification of a series of seven vertex-positive upward deflection "bumps" (Jewett, Romano, & Williston, 1970), the origin of wave I is the only potential on which investigators have made a unanimous agreement. Recent research shows that both waves I and II are generated by the distal and proximal portions of the eighth cranial nerve, respectively, at least in human subjects (Moller & Moller, 1985). Thus, the focus of the present investigation is placed on the peripheral auditory system, particularly the initial neural aspect of the auditory nerve that leads into the internal auditory meatus. The internal auditory meatus as well as the cerebellar pontine angle (CPA), are common sites of lesions for the peripheral pathway.

By studying wave I' and its relationship with wave I, an insight will be gained into the status of the physiologic patterns generated by the inner hair cells (IHCs) as they send their signals to the auditory nerve.

Although only normal-hearing female adult subjects are used in this study, inferences can be made to normal-hearing adult male subjects, as well as pediatric and pathologic ears. Capacity to generalize from the design of this study is based on the random and independent selection of subjects from the population, which gives the study strong external validity. In addition, the diagnostic importance of this investigation is demonstrated by its focus on general anatomical areas thought to generate the cochlear microphonics (CM), summating potential (SP), CAP, and action potential (AP) which are key features for diagnostics purposes. For example, loss of hair cells has been reported to cause a marked reduction of SP (Picton & Fitzgerald, 1983). Furthermore, the CAP and wave I' have the potential of diagnosing malfunction of the efferent fibers or nuclei of the superior olivary bundles, since this latter structure sends its efferent extensions into or near the IHCs by synapses.

In investigating the change in magnitude of waves I' and I, and in comparison to the remainder of the short latency evoked potentials, the I' technique may hold promise for more precise diagnostic information about the cochlear and the nerve. Identification of waves I' and I is important since it is somewhat difficult to assess the integrity of the brain-stem function using inter-wave peak latencies of waves I-V, and I-III, as well I/V amplitude ratio. For example, evaluation of the brain-stem

transmission time (BTT) cannot be reliably completed without the presence of wave I of the BAEP or N_1 of the CAP (Sohmer, 1983; Fabiani et al, 1979).

By distinguishing the wave I' from the DC shift that results as the SP, this investigation perhaps holds promise for a better understanding of the SP/AP ratio which is currently used for evaluating patients with Meniere disease. At the present time the nature, source, and significance of the SPs are only partially understood. The fact that many patients with inner ear disorders tend to have a wave I which is larger than wave V, may explain possible malfunctions of the efferent feedback system which has its origin at cochlear bundles. This latter observation could also be indicative of the notion that waves which follow wave I are at times attenuated. Thus this investigation seeks to offer an explanation as to the status of cochlear bio-eletrical events.

Limitations of the Investigation

Since this investigation is being conducted using human subjects, it is not possible to investigate wave I' with a neurotoxic chemical, such as tetrodotoxin (TTX). This chemical substance has been found to be effective in distinguishing the non-neural from the neural components of the auditory pathway in species such as the cat (Moore, Caird, Klinke, & Lowenheim , 1988), the guinea pig (Xi, Dolan, & Nuttall, 1989; Dolan, Xi, & Nuttall, 1989), and the cricket acheta domesticus (Venkatarao, Moore, & Lowrie, 1990). These showed that TTX reduced the amplitude of the wave N1 in animals while the EPSP or

EPSP-like response remained unaffected. Wave N1 in animals is thought to be an equivalent to wave I in human subjects. Based on experimental animal studies such as these, it is assumed in the present study that wave I' in humans would behave in a similar manner if treated with TTX.

It is also important to note that the size of the head of most experimental animals is much smaller than the human head. Thus, the length of the human auditory nerve has been found to be about five times longer than that of the cat (Buchwald & Huang, 1975; Lang, 1981). This would appear to explain the findings that while the generator of wave II of the BAEP is at the peripheral part of the auditory nerve in human subjects, the cochlear nucleus of the central nervous system has been found to generate this potential in experimental animals. From these data it is apparent that the neural impulse transmission in these animals is different from that of humans. Consequently, extra caution is necessary whenever inferences are made from evoked potential investigations of experimental animals.

The paucity of (ECochG) studies on human subjects in which the active electrode is placed in close proximity to the generator, motivated the experimenter in this investigation to use far-field recording techniques in which an ear canal electrode is placed in the external auditory meatus. This technique tends to reduce the amplitude of wave I, when compared to wave I which is obtained from an electrode placed at the promontory (Coats, 1983, 1974; Simmons, & Beatty 1962).

CHAPTER II

Historical and Current Status of Wave I' of the BAEP

Wave I' of the Auditory Brain-Stem Response was first reported by Hughes, Fino, and Gagnon (1980 and 1981). Subsequently, Benito, Falco, and Lauro (1984) observed a similar evoked potential which they labelled wave "O". In 1984, Moore and Semela also observed the potential and named it BI (before wave I, Moore, & Semela, 1985). Initially, Hughes et al postulated that the source of the potential was the dendrites of the auditory nerve and thus they speculated that wave I' may be an EPSP (therefore, the label, dendritic potential, was employed). However, it remained uncertain as to whether the potential arose from the auditory nerve dendrites. To accommodate this uncertainty, Moore and Semela (1985) thought it was necessary to use a descriptive phrase, namely, "Before wave I" (abbreviated BI), since the potential preceded wave I of the BAEP. In subsequent years, however, Moore and co-worker decided to use Hughes' label, I', since several investigators used the identifier BI for referring to the aural interaction potential of the BAEP.

Recently, the use of pharmacologic agents in animal experiments provided additional evidence that wave I' could presumably be a neural response. Moore et al (1988) and Klinke, Caird, Lowenheim and Moore (1988) used TTX to block fast sodium channels of axons in auditory nerve afferent fibers of the cat. Their findings suggested that wave Po in animals, or possibly wave I' in humans, originates from

afferent fibers of the auditory nerve. Dolan et al (1989) administered TTX at the guinea round window membrane. Their pre- and post-treatment analyses of responses showed that TTX obliterated the CAP, while an EPSP-like response remained unaltered. These studies make it imperative that wave I' in humans receive close examination for research and clinical pursuits.

In order to understand the occurrence of wave I' of the BAEP, it is essential to examine the environment in which the potential occurs. Wave I' potential may be appreciated in the context of its proximity to responses such as the synaptic and coupling potential. These responses may be viewed in accordance with the following major functional features: synaptic potentials, coupling potentials, pre- and post-synapses, and excitatory postsynaptic potentials.

Synaptic Potentials

Four types of synapses in the organ of Corti have been suggested (Pujol and Lenoir, 1986): (a) auditory dendrites (between IHCs and radial afferent fibers); (b) axodendritic synapses (between the lateral efferent endings and the auditory dendrites); (c) synapses between the OHCs and the spiral afferents; and (d) Axosomatic synapses (between medial afferent endings and OHCs).

This classification of synapses elaborates on the traditional functional categorization of the organ of Corti nerve fibers (afferent and efferent). The potentials of each class are outlined in the subsequent sections.

Auditory Dendritic Synapses

IHCs have been found to be innervated by fibers from type I myelinated ganglion cells in cats and humans (Kiang, Northrup, Liberman, & Ryugo, 1982; Morrisson, Schindler & Wersall, 1975). The fibers become unmyelinated as they enter the organ of Corti. The demyelinazation process earns them the name dendrites. From the habenula perforata, the dendrites run radially toward the basal end of the IHCs.

Innervation of the IHCs is complex and seem to be species-specific. Liberman (1980a, 1980b) identified two kinds of afferent medial fibers in the cat. These fibers were found to make different kinds of contacts, for instance, at the pillar or modiolar of the IHCs. The auditory dendritic synapses have pre- and post-synaptic membrane structures which are surrounded by minute vesicles (Smith and Rasmussen, 1963) which form clefts of about 20 nm in humans (Nadol, 1983a, 1983b) or 10 nm in the cat (Liberman, 1980a, 1980b). Saito (1980) reported that these clefts are occupied by a granular substance that tends to be thick on the postsynaptic membrane.

The synaptic bodies vary in terms of their size and shape. These differences are thought to be associated with individual species features (Pujol & Lenoir, 1986), with physiologic status of the hair cells (Jorgensen, & Flock, 1976), or with structural variation (Sobkowicz, Rose, Scott, and Slapnick, 1982; Nadol, 1983a, 1983b). For example, while most species showed that there was only one synaptic body adjacent to each afferent fiber, Nadol (1983a) identified up to six synaptic bodies for every afferent ending in a 64-year-old human male subject.

Despite the diverse nature of synaptic body distribution between and within species, the following patterns tended to hold: (a) immaturity (owing to factors such as young age) seemed to positively correlate with multiple synaptic bodies; (b) reduced number of presynaptic bodies seemed to relate to the normal physiology of the IHC synapses. Increased number of presynaptic bodies during maturation or the aging process is suggestive of malfunction of the IHCs.

Efferent Synapses at the IHC Level

These are unmyelinated efferent axons situated below the IHCs. They form an inner spiral bundle that synapses with the radial afferent dendrites (Iurato, 1974). Their origin is in the lateral superior olive, and they have been found to terminate into the ipsilateral cochleae of cats and rats (Warr, 1980; Warr and Guinan, 1979; White & Warr, 1983). Upon entering the cochleae, the fibers branch both basally and apically, then run underneath the IHCs.

Axodendritic efferent synapses form the main part of the IHC level. There are other minor constituents of the IHC synapses. These include those situated between efferent fibers and IHCs synapses. The fibers that connect the efferent fibers and the IHCs are uncommon in adults (Pujol and Lenoir, 1986). They have been found only in exceptional cases among cat cochleae (Spoendlin, 1972; Liberman, 1980b). It was found, however, that although direct contacts between efferent varicosities and IHCs exist in humans and guinea pigs, they are by no means typical. The second type, efferent-efferent synapses were first reported by Liberman in 1980(b). They are thought to be located between the medial and lateral efferent fibers that supply OHCs. In addition, it has been suggested

that these synapses possibly provide links between two chemically defined efferent varicosities.

The major functions of axodendritic synapses include providing a link between afferent dendrites and efferent varicosities. Efferent varicosity is filled with two kinds of vesicle, namely, clear and granular vesicles. Granular vesicles comprise dense cones of between 70 and 120 nm in diameter, whereas clear vesicles have a shorter diameter range of between 20 and 50 nm.

OHC-Afferent Synapses

Innervation of the OHCs is very different from that of the IHCs because of characteristics such as (a) reduced number of efferent neurons supplying the OHCs; only 5 to 10 percent of the neurons reach the OHCs in the cat (Spoendlin, 1969) or 10 to 15 percent in the guinea pig (Morrisson, et al, 1975); (b) ganglion neurons that send fibers to OHCs seem to be all type II unmyelinated cells (Kiang et al, 1982; Perkins & Morest, 1975; Spoendlin, 1979); (c) within the organ of Corti, dendrites that connect the OHCs follow a different route from that of the IHCs. They spiral between the Deiter cells after crossing at the floor of the tunnel of Corti.

OHC-Efferent Synapses (Axosomatic)

These are large axosomatic synapses that are formed by efferent fibers and the basal pole of the OHC. Warr (1980) found in the cat that most of the fibers in efferent-OHC synapses had their nuclei in the contralateral trapezoid bodies. The fibers are myelinated up to the habenula perforata. Nadol (1983a, 1983b) discussed these synapses on the bases of findings made on the inner ears of cadavers.

The presynaptic part is occupied by clear microvesicles. These microvesicles are of regular size, about 30 nm in diameter. Unlike the efferent synapses of the IHCs, the axosomatic efferent synapses of the OHCs rarely have granular vesicles. Mitochondriatic substances are situated in the basal part of the synapses. Whereas the area around the presynaptic membrane commonly contains clusters of vesicles, the postsynaptic membrane is completely underlaid by a sub-surface cistern of reticullum.

In studying axosomatic efferents of the OHC synapses (pre-, post- and cleft synapses), Nadol (1981, 1984) found that the junctions had dual synaptic specialization and pre- and postsynaptic features on the same side. Supporting Nadol's hypothesis on axosomatic efferent-OHC synapses, Pujol and Lenoir (1986) suggested that OHCs possibly developed cisterns in preparation for arrival of efferent fibers, however, the fibers never reach the cistern.

Transmission of auditory signals may by appreciated when related to the above synapses. Integrity and competence of these synapses play an essential role in the neural output of the auditory system. For example, malfunctioning of the efferent synapses (i.e., axodendritic and axosomatic synapses) is thought to result in an abnormally large wave I of the ABR (Musiek, 1989). As related to electro-physiologic diagnostics, such an abnormality may be detected either by visual inspection or by analysis of the wave I to V ratio. It is within these synaptic potentials that the coupling, excitatory, and inhibitory potentials may be distinguishable.

Coupling Potentials

Coupling of acoustic energy occurs during hair cell stereocilia displacement after the organ of Corti has been stimulated. In acquatic species, such as fish and amphibians, hair cells of the lateral line organs have been found to be of two fundamental kinds, epidermal and canal. Coupling in these organs occurs through water movement, as the cupula and hair cell are displaced. Thus, coupling and transduction of potential acoustic energy depends, for the most part on the orientation of the cells in certain individual kind of an organisms. For instance, mammals have types I and II hair cells such that the inner and the outer hair cells are set in motion by an acoustic force.

The focus of mammalian studies is generally placed on specific roles of different parts of the hair cells as well as their linkages. These include the tectorial membrane, reticular lamina, and spiral ganglion fibers. In this manner, an attempt is made to understand how transduction of acoustic stimulus occurs in mammals. Studies on mammalian specimen pointed to the effect that: (a) kinocilia are absent in adults; (b) complete coupling seems to occur only between the outermost row of the OHCs and the tectorial membrane (Lim, 1972); (c) IHCs stereocilia either seemed to have a loose mechanical coupling with the tectorial membrane (Hoshino, 1976) or had no direct contact (Kimura, 1966).

Based on these studies, the coupling system in the inner ear remains open to multiple physiologic questions. It is currently thought that if coupling does not occur between the hair cells and

the covering membranes in the superior position (reticular lamina, gelatinous, or tectorial membranes), then fluid below the tectorial membrane must be responsible for transducing basilar membrane velocity, not displacement (Nuttall, 1986). The latter view is supported by the findings that myosin and actin found in hair cells, are elastic (DeRosier, Tilney, & Flicker 1980; Drenckhahn, Kellner, Mannherz, Groschel-Steward, Kendrick-Jones, & Scholey, 1982).

While Spoendlin's findings suggested that IHCs possibly resulted in sharp tuning curves, Evans and Wilson (1973) attempted to explain how coupling between the basilar membrane and hair cells occurred. These investigators considered coupling as a second filter in the cochlea. In addition, Khanna and Leonard (1982) investigated basilar membrane tuning capacities and coupling potentials in the cat. They analyzed the effects of amplitude as a function of frequency while sound pressure level was kept constant. These investigators were disappointed that they did not see a cochlea without signs of trauma in their inner ear research. Traumatized cochleae tended to produce tuning curves that are similar to those of the auditory nerve fibers. The fine difference was that the auditory nerve tuning curves had larger peaks and sharper tuning. As the damage to the cochlea increased, Khanna and Leonard found that: (a) increased sound pressure level occurred in the negative peak; (b) gradients for the low and high frequencies diminished; (c) the peak grew broader; (d) there was a shift of the peak to the lower frequencies; (e) a decrease of 10 to 15 dB occurred around the plateau area, below the frequency.

Furthermore, a peak with reduced amplitude was observed in the frequency domain around the cutoff region. Thus, the basilar membrane mechanical responses yielded a small peak. Rhode (1978), however, had previously observed a large basilar membrane response peak. In essence, magnitude of both peaks observed by these investigators were smaller than responses found in sharply tuned auditory nerve fiber activities (Kim and Molnar, 1975). Interpretation of results such as these require a close analysis of such factors as the physiological vulnerability and the nonlinear nature of basilar membrane motion.

Synapses [Presynapses and Postsynapses]

An understanding of excitatory postsynaptic potentials (EPSPs) and inhibitory postsynaptic potentials (IPSPs) requires an insight into the notion of a synapse. Therefore, a brief review of the nature and function of the synapse in the nervous system is in order.

The term synapse was first used by Sir Charles Scott Sherrington to refer to a junction between an axon and a nerve cell or between an axon and a gland cell (Schmidt, 1983). Using a different classification system than that of Pujol and Lenoir (1986), synapses may be divided into two groups, the chemical and electrical synapses (Schmidt, 1983). In both chemical and electrical synapses impulses are transmitted from the axon to the next cell almost 100 percent of the time. That is, signals are transmitted from presynaptic to postsynaptic parts of the axon and the cell respectively.

A chemical substance released during the action potential may have excitatory or inhibitory effects. Electrical synapses, unlike chemical synapses, are relatively uncommon. If they occur, the action potential elicits inhibitory or excitatory interception of chemicals.

In summarizing the function of the synapses, Schmidt identified the following characteristic features: (a) valve action, by providing gaps along the fiber tracks, the central nervous system (CNS) operates in an effective way; (b) synaptic potentiation the more the number of synapses along the fiber track, the greater the efficacy and the larger the synaptic potentials.

Excitatory Postsynaptic Potential (EPSP)

EPSPs are most relevant to the study on the wave I' of the BAEP. They may be explained in terms of the physiology of the motoneuron, a concept that applies to most aspects of the nervous system. The motoneuron is estimated to consist of about 6,000 axosomatic and axodendritic synapses. Some of these synapses are excitatory, whereas others are inhibitory. Further, synapses cover the axon and the axon hillock. When an acoustic stimulus reaches the inner ear, depolarization of the hair cell membrane takes place. A number of afferent neurons fire collectively. Depolarization of this nature which "produce a conducted action potential" (Schmidt, 1983, p. 59) is known as an EPSP. EPSPs are distinguished from end-plate potentials (i.e., at the end of neuromuscular junction) in terms of the number of synapses activated. Whereas the end-plate potentials reflect response

from a single synapse, EPSPs are elicited from an accumulation of a number of synapses. The amplitude of depolarization is usually directly proportional to the number of afferent neurons excited. In this way afferent volley excitation can be determined.

Studies show that the EPSP originates from a short conductance increase for small cations (that is, ions that migrate to the cathode). This view attempts to explain the ionic mechanism of the EPSP; the membrane time constant of the motoneuron has been found to be 1-2 ms (Eccles, 1966, 1969).

The effectiveness of impulse transmission has also been studied with somatic and dendritic synapses. The spread of EPSPs near the axon hillock was thought to have greater impact on the neuron than on the more distant dendritic synapses. This view arose from the observation that the EPSP spread over the cell membrane was relatively passive. However, compensation for the disadvantage imposed by the distance within a neuron is compensated by the appearance of very large dendritic EPSP (Schmidt, 1983). Kandel (1977) pointed out that the differences in EPSPs spread may be due to cable properties arising on the side of the postsynapse.

The question of the cell size and its capacity to be excited has been considered. If other physiological functions are kept constant, the following rules apply: (a) the smaller the motoneuron, the greater its excitability capacity and the harder it is to inhibit.
(b) Conversely, the greater the motoneuron, the smaller its capacity to be excited, and the more readily it is to be inhibited (Henneman, Somjen, & Carpenter, 1965a, 1965b). Further, neural excitability is possibly a function of an individual neuron. Thus, current transmit-

ted through the subsynaptic membrane of a small cell gives rise to a larger EPSP than is commonly found in larger cells.

Studies on the EPSPs of different nerve cells remain incomplete and inconclusive. There is, however, a trend toward the following observations: (a) the EPSPs previously described occur in neurons of the CNS; (b) while short as well as long rise/fall times have been found, as a rule, moto-neurons displayed shorter durations than other EPSPs; (c) peripheral sympathetic ganglion cells have been observed to be very slow.

INSTRUMENTATION VARIABLES

Definitions of Stimulus-Response Parameters in the BAEP

Stimulus Intensity and Latency. Intensity refers to the level in decibels at which an acoustic stimulus is presented. Latency is the time period in milliseconds between the onset of the acoustic stimulus (such as a pulse) and specific point on the waveform. Thus, latency refers to an interval on the waveform from a definite starting point. This interval is also referred to as an absolute latency or implicit time. The units of absolute latency in evoked potentials are also commonly represented in milliseconds. Related to absolute latency is the time separation between two peaks on the waveform, which is called interwave interval (IWI) or interpeak latency (IPL).

Amplitude and Morphological Responses. Amplitude is the magnitude of the difference between the minimum or the maximum and the equilibrium during vibratory notion initiated by an acoustic stimula-

tion. Amplitude if usually measured using milli- or microvolts along the Y-axis on an oscilloscope. As current and voltage change over time, waveforms are traced on an output medium, which comprises the shape or morphology of evoked responses. Thus, latency, amplitude, and morphology are the main features by which responses are evaluated.

In general, there is an inverse relationship between the stimulus intensity and the latency of the response. Although an inverse relationship between variables has been observed in all neural systems (Schwartz & Berry, 1985), the following specific variations have been identified: (a) slow rising postsynaptic potentials cause prolonged synaptic transmission latencies (Picton, Woods, Baribeau-Braun, & Healey, 1977); (b) as the stimulus intensity is decreased below 50 dB nHL, waves I and III of the BAEP become unstable (Jewett et al., 1970); (c) wave V remains less affected as shown by a slight change in morphology and reduction of intensity. Furthermore, research on stimulus intensity and its relationship to absolute latency, is fairly consistent with minimal variation of some stimulus parameters. For identification of wave I, intensity as high as 70 dB SL is recommended (Schwartz & Berry, 1985). In general, a repetition rate of fewer than 12 stimuli per second, polarity of rarefaction, and vertical montage of electrode (Cz to earlobe) were considered as most ideal in clinical diagnostic evaluations.

Filter Effects on BAEP

Bandpass filtering of acoustic energy is a method of improving signal-to-noise ratio. By so doing, an attempt is made to reduce the

competing electrical activity (e.g., EMG) which is about 100 times greater than the BAEP (Davis, 1976; Skinner, 1978; Schwartz & Berry, 1985). It is, therefore, important to select a bandpass that will enhance the waveforms maximally with minimal distortion.

Investigators in different laboratories have used various bandpasses to determine the most efficient filter settings in eliciting BAEP. Twenty-four of such studies are listed in table II-1. Based on these filter settings, it is apparent that the most preferable high cut-off-point, for clinical studies, lies between 2,500 and 3,500 Hz. There was, however, a significant disagreement as to the most suitable low cutoff point. From table II-1 it can be seen that there was a wide variance of selection for the low cut-off-point. For most of their clinical studies, Glasscock, Jackson, & Josey (1987) reported obtaining satisfactory BAEP enhancement with the high pass setting of 50 or 100 Hz.

The criterion for the choice of filter settings is dependent on several variables. For example, factors such as the noise interference from myogenic activity of the desired bio-electrical potentials are important considerations. Several studies focused on the evoked responses in terms of spectral energy of different peaks of the BAEP. These studies have suggested that the main spectral components of BAEP are found in the 50-1,000 Hz range (Laukli & Mair, 1981; Kevanishvili & Aphonchenko, 1979; Suzuki & Horiuchi, 1977; Elberling, 1979, 1976).

According to Kenavishvili and Aphonchenko (1979) the main spectral components of waves I and II are found between 400 and 1000 Hz. Wave III resides within the 100 and 900 Hz range, waves IV through VI are

Table II-1. Differences in Filter Bandpass used in Recording the BAEP Across 24 Published Reports

Investigator	Filter Bandpass (Hz)
Borg and Lofqvist (1982)	10 - 2500
Maurer et al., (1982)	300 - 3200
Cacace et al., (1980)	150 - 1500
Cacace et al., (1980)	150 - 3000
Chiappa et al., (1979)	300 - 3000
Galambos and Galambos (1979)	150 - 1500
Gilroy and Lynn, (1978)	150 - 3000
Jerger and Mauldin, (1978)	300 - 3000
Rosenhamer et al., (1978)	180 - 4500
Selters and Brackmann (1977)	30 - 3200
Elberling, (1976)	5 - 5000
Hyde et al., (1976)	100 - 4000
Moller and Blegvad, (1976)	150 - 4500
Zollner et al., (1976)	350 - 4000
Starr and Achor, (1975)	100 - 3000
Picton et al., (1974)	10 - 3000
Hecox and Galambos, (1974)	80 - 3000
Amedeo and Shagass, (1973)	10 - 8000
Martin and Coats, (1973)	80 - 1000
Terkildsen et al., (1973)	500 - 4500
Lev and Sohmer, (1972)	250 - 5000
Jewett and Williston, (1971)	10 - 2500
Jewett et al., (1970)	300 - 2000

distributed from 100 to 500 Hz. The importance of selecting appropriate filter settings in BAEP studies is stressed by the fact that responses may be obscured by factors such as the size of the bandwidth and the rates at which filter roll-off occur. In addition, inappropriate selection of filter setting has the potential of prolonging latencies. These prolongations are due to phase distortion which is related to both the gradient and the cut-off frequency of the bandpass.

While the effects of filtering on the major features of BAEP waveforms have not been fully studied, Jewett and Williston (1971) found no significant differences between responses recorded on-line with filter bandwidths covering a wide range (10-10,000 Hz) and off-line recording from an FM tape recorder with a low pass filter setting of 2,500 Hz. These investigators, did, however, find a strong relationship between the bandwidth size and the wave form latencies. In conformity with Mendel and Goldstein (1969), Jewett and Williston (1971) found that the high frequency cut-off filter markedly influenced the latency of the early waves of the brain-stem. Considering the fact that the first five waves, at intensities levels higher than 70 dB SL, emerge within 5 ms after presentation of click stimulation. Jewett and Williston recommended that the minimum high frequency cutoff of no less than 1000 Hz be used in BAEP data collection.

Different studies have shown that filter settings have significant influence on latency, amplitude, and phase on the early latencies of the BAEP. Stockard, Sharbrough, and Tinker (1978) found that an increase of low frequency filter setting from 100 to 300 Hz

progressively decreased the latency of the waves. They also observed that the IV/V amplitude ratio decreased quickly. Cacace, Shy, and Satya-Murta, (1980) compared the effects of the bandpass filters of 150-1,500 Hz and 150-3,000 Hz, where the slope of the bandpass was 12 dB per octave for both conditions. Their study suggested that the narrower the bandpass filter of a 150-1,500 Hz caused longer latencies of the waveforms than the 150-3,000 Hz bandpass filters. Chiappa, Gladstone, and Young (1979) varied high pass filter from 100 to 300 Hz, while the low pass was kept fixed at 3,000 Hz. These studies concluded that as the high pass point shifted from 100 Hz or 150 Hz toward 3,000 Hz, the size of wave amplitudes decrease. In addition, it is noteworthy that these studies focused on wave the IV/V complex. Such a focus is based on obvious reasons; the wave IV/V complex is usually the largest response among the early potentials, and it remains relatively insensitive to intensity level changes.

In summary, the effects of bandpass filter settings are best illustrated in figures 1 and 2, documented by Schwartz and Berry (1985). The graphs in these figures may be interpreted as follows: low-frequency filter cut-off was varied while high-frequency filter was constant at 3,000 Hz. These were results obtained from normal-hearing adults. Click stimuli were presented at 75 dB nHL at the rate of 11.1 per second using rarefaction stimulus polarity. These graphs show that as the low-frequency setting increases, wave latency decreases. Thus, shortening of latencies were more noticeable in the cephalic than in the caudal region. Similarly, increase in the low-frequency filter setting appeared to be directly proportional to the waveform amplitude. Narrower bandpass filter settings (150-3,000 and

300-3,000 Hz) yielded best responses, with the 150-3,000 Hz showing the wave I most distinctly.

Second, high-frequency filter cut-off was varied while low filter was kept constant at 150 Hz. From these graphs it is apparent that: (a) less than 1,500 Hz high-frequency filter settings completely obscure morphology of the waveform; (b) the waveform filtered through 150 and 1,500 Hz yielded the most lucid wave peaks with minimal ambient noise; (c) in contrast, Cacace et al.(1980), found that the 150-1,500 Hz bandpass tended to prolong latency wave peaks. These investigators recommended the use of 150-3,000 Hz for clinical diagnostic purposes.

In support of the findings stated above, Laukli and Mair (1981) studied the effects of analog filtering BAEP in humans as well as animals (cats). Two points became clear from their study; namely, (a) as the low cut-off point is increased from 2 to 100 Hz, the slow component of the responses diminishes. Furthermore, a decrease in the peak latencies occurred; (b) as the high-frequency cut-off is decreased from 5,000 to 1,000 Hz, latency increments were observed across the wave components.

A perusal of the results of the literature on the effects of filter settings in eliciting brain-stem evoked responses makes it obvious that full knowledge of how filters operate is essential. Response-filtering affects all aspects of evoked potentials. For instance, distortion of morphology, amplitude, and latency of waveforms caused by the filtering system may lead to incorrect clinical and research interpretations. With the advent of modern, commercially available, ABR digital filter-equipped instrumentation,

phase shift can be minimized.

Effect of Stimulus Polarity on the BAEP

Phase or stimulus polarity in eliciting of BAEP comprises three experimental conditions: rarefaction, condensation, and alternating. Short duration acoustic stimuli, such as an electrical square wave of 100 to 200 microseconds, are delivered to the ear via a transducer. In a rhythmic pattern, the diaphragm of an earphone moves in a synchronized way with the tympanic membrane. Rarefaction is a condition in which the initial movement of the transducer diaphragm is away from the tympanic membrane (i.e., the eardrum deflects), while the transducer diaphragm movement bulges toward the tympanic membrane when condensation occurs. Alternating condition involves the combination of rarefaction and condensation polarities.

Studies on phase have focused on whether different polarities had different effects on evoked potentials. The criterion for determining these differences had to do with the waveform morphology, latency, and amplitude. Terkildsen, Osterhammel, and Huis in't Velde (1973) were among the first to investigate if such differences existed among BAEP. They found no consistent differences between rarefaction and condensation click stimuli for the early responses. Their findings were, nonetheless, contradicted by Ornitz and Walter (1975) who, on the basis of examining wave V latencies, concluded that rarefaction clicks constantly produced a 0.4-0.8 ms shorter latency than condensation clicks. Subsequently, additional research was initiated on the effects of polarity on wave V (Rosenhamer, Lindstrom, and Lundborg,

1978; Stockard, Stockard, Westmoreland, & Corfits, 1979; Kevanishvili & Aphonchenko, 1981; Borg & Lofquist, 1982; Ruth, Hildenbrand, & Cantrell, 1982). These investigators found no consistent results that showed the differences between the two polarities; thus, they were in agreement with the findings made by Terkildsen and co-workers (1973).

In contrast to studies that investigated wave V, several of these investigators (Kevanishvili and Aphonchenko, 1981; Ruth et al, 1982; Stockard et al., 1979) found polarity differences in terms of the major features. Rarefaction yielded superior output resolution, decreased latencies, and increased amplitudes.

An alternating phase has been used in data collection in order to minimize the effects of electrical artifacts as well as cochlear microphonic responses. Alternating polarity, however, has been found to cause latency shifts. It has been pointed out, however, that these waveform alterations were less than those caused by condensation clicks (Schwartz & Berry, 1985).

Effects of Repetition Rate on BAEP

Click repetition rate refers to the rate at which the presentation of stimuli occurs within one second. Jewett and Williston (1971) reported that click repetition rate had deleterious effects on the BAEP. These investigators found that repetition rate had effects on the early evoked potentials. They showed that as the repetition rate increased from 2.5 to 50 stimuli per second waveform, morphology progressively changed. Furthermore, subsequent research showed that as the repetition rate increased, amplitude decreased (Zollner,

Karnahl, & Stange, 1976; Pratt & Sohmer, 1976).

Studies on click stimulus rate strongly suggest the use of 20 or fewer stimuli per second for clinical purposes. This point is illustrated by ten studies shown in table II-2, in which 80 percent employed stimulus repetition rates of 20 or fewer. Other investigators insist on the use of slow rates of equal or fewer than 10 for diagnostic purposes Chiappa 1983; Schwartz & Berry, 1985). The following points are suggestive of the use of slow repetition rate in eliciting BAEP: (a) higher than 10 stimuli per second tend to yield poor resolution. The faster the stimulus rate the greater the loss in waveform resolution; (b) as a rule tumors that are detected through the use of fast repetition rates do not escape detection through the use of slow rates.

There are also studies showing that an increase in repetition rates affects different portions of the ABRs differently. Schwartz and Berry (1985) reported that repetition rates higher than 20 stimuli per second resulted in reduced amplitudes of waves I, II, and III of the BAEP, while wave V showed no discernible alteration until a 30 stimuli per second rate had been exceeded (see Appendix A). Hyde, Stephens and Thornton (1976) reported similar results. These investigators used 2-20 and 2-50 stimuli per second in their experiments. They suggested that a rate of 30 stimuli per second was critical for the wave IV-V complex.

van Olphen, Rondenburg, and Verwey (1979) found that an increase of repetition rate from 2.5 to 80 stimuli per second resulted in: (a) a uniform decrease of N2-N4 amplitudes; (b) amplitude of N5 remained unaffected; and (c) at a repetition rate that is greater than 10

Table II-2

REPETITION RATES SUGGESTED IN VARIOUS BAEP LABORATORIES

Investigator(s)	Repetition Rate (stimuli per second)
Coats and Martin (1977)	20
Davis (1976)	20
Fria and Sabo (1979)	10-30
Glasscock et al., (1979)	8
Jerger et al., (1970)	20
Mokotoff et al., (1977)	33.3
Selters and Brackmann (1977)	20
Starr and Achor (1976)	8
Starr and Hamilton (1976)	10
Stockard and Rossiter (1977)	10

stimuli per second, a latency increase of 0.4 ms appeared throughout all BAEP peaks. These findings provided a more detailed analysis of latency and amplitude of BAEP than was shown by Pratt and Sohmer (1976) and Zollner et al. (1976).

Appendix A shows a graphical representation of the repetition rate series with emphasis on the behavior of wave V as repetition rates increase from 21.1-81.1 Hz. These results are consistent with studies made by several investigators (Gerling and Finitzo-Hieber, 1983; Ruth et al, 1982; Picton, Stapells, & Campbell, 1981; Don, Allen, & Starr, 1977; Hyde et al., 1976). They indicated that the latency of wave V increased progressively as repetition rate increased. Appendix B shows Weber and Fujikama (1977) findings in which rapid repetition rates significantly affect intensity-latency function in a normal-hearing listener.

From these studies it is apparent that slow repetition rates are desirable for clinical as well as research application. Furthermore, this suggests that slow repetition rates reveal clear waveform morphology with neither reduction of amplitude nor alterations of latency. Contrary to this view, there are those who advocate the use of fast rates of stimulus presentation so as to identify incipient disorders (Sininger & Don, 1989; Gerling & Finitzo-Hieber, 1983; Robinson & Rudge, 1977).

In negating the use of fast repetition rates, Glasscock and co-workers (1987) stressed the need to diagnose patients on the basis of clear and reliable waveform morphology. They argued that, while fast repetition rates have the advantage of obtaining thresholds quickly, documentation on patient testing using fast repetition rates was

insufficient as to be fully adopted as a diagnostic technique. Glasscock and co-workers also contended that the use of a repetition rate of 40 stimuli per second may be appropriate only for screening for the threshold of wave V.

Fast stimulus rates have been implicated in many situations where data need to be collected. These included data gathered from the normal as well as pathologic ear. According to Thornton and Coleman (1975), normal-hearing persons showed latency increase adaptations if exposed to acoustic stimulus clicks at fast repetition rates. Apparent cause of this behavior is possibly the cumulative loss at low and high brain-stem levels. Another study which supported the view that increased repetition rates may be a powerful diagnostic tool, is that of Daly, Roeser, Aung, and Daly (1977). In addition, Josey (1985) pointed out that patients with VIIIth nerve tumor often reveal abnormality if stimulated at fast repetition rates. On the other hand, Gerling and Finitzo-Hieber (1983) found that fast repetition rates may be indicative of abnormality in patients with CNS malfunction.

In the interest of the present study, and considering the fact that fewer than 12 stimuli per second repetition rates have been recommended (Schwartz and Berry, 1985) to preserve clarity and magnitude of waves I and III, slow rates seemed desirable. This view is necessitated by the fact that wave I′ which the present study is investigating, arises in the vicinity of wave I, and it was essential that optimal output of waveforms be obtained.

Effects of Masking on the BAEP

An understanding of how forward masking affects the cochlear nerve requires an insight into at least three other concepts, namely, masking in general, adaptation, and fatigue. All three of these terms influence the behavior of the auditory system when continuously stimulated with sound.

Auditory Adaptation and Auditory Fatigue:

These two concepts are closely related, that they are often used interchangeably, which is incorrect (Ward, 1973). Although these terms describe different physiologic events, they originate from the same sound source (sustained and/or intermittent acoustic stimulation) at threshold or suprathreshold intensity levels. Both auditory adaptation and auditory fatigue were present symptoms that may be identified with the cochlea and/or VIII th cranial nerve. Furthermore, both phenomena are time-dependent and, therefore, characterized by a temporary threshold shift (usually, but not always, a reduction in response), as a result of continued acoustic stimulation.

In an auditory fatigue condition, responses diminish progressively as acoustic stimulation is continued. Conversely, in an adaptation condition acoustic stimulation usually produce response variations until a plateau is reached. No further changes occur after a plateau is attained.

In examining the concept of auditory adaptation, A.M. Small (1963) identified five psychophysical methods of measurement which

are sensitive to changes that occur during auditory adaptation. These factors were related to loudness, that is, the absolute threshold of hearing, the masked threshold, and the changes that occur at suprathreshold levels, and were referred to as delta-I. Furthermore, the factors were related to pitch, that is, pitch shift as seen in diplacusis, apparent location shift as evidenced in dichotic listening, or delta-F. Whereas the phenomenon of auditory fatigue appears to use reserved energy, adaptation may be thought of as an adjustment of the auditory system to prolonged acoustic stimulation.

Fatigue comes about as a result of two variables, intensity and duration. High intensity of acoustic stimulation may lead to significant suprathreshold shifts in a short time. In contrast, low intensity stimulation (e.g., at threshold) may cause threshold shifts over a long period. Similarly, high intensity acoustic exposure over a long period may have more intense effects on the inner ear.

In demonstrating how prolonged suprathreshold acoustic stimulation may produce temporary threshold shift (TTS), Ward, and Glorig (1959) exposed human subjects to a 2,400-4,800 Hz band of noise at 85 and 90 dB SPL for about two hours. Similary, Gisselsson and Sorensen (1959) explored the effects of acoustic stimulation on cochlea potentials of guinea pigs. Their findings are as follow: (a) low stimulus intensities appeared not to have an influence on the amplitude of cochlea potentials; (b) a decrease in amplitude of the potentials occurred only after exposures exceeded 95 dB SPL (re-human threshold); (c) a reduction in cochlear potential amplitude was interpreted to be due to fatigue, not adaptation; (d) the longer the duration of acoustic exposure, the longer the need for recovery time; (e) while white

noise stimulation was found to affect cochlear potentials, pure tones of 500, 1,000, and 2,000 Hz had no direct effect; (f) a 5,000-20,000 Hz noise bandwidth demonstrated maximal effect of amplitude on the cochlear potentials. Thus, auditory fatigue appears to require a higher intensity level than auditory adaptation.

Pollack (1952) studied the effects of filtered noise on adaptation. His experimental conditions included continuous as well as intermittent noise. Acoustic stimuli were presented at supra-threshold levels. The results of the study showed that an increase in noise bandwidth size produced an increase in adaptation to the noise signal.

The increment patterns observed were similar to the changes in loudness as the bandwidth increased. Subsequently, Carterette (1955, 1956) made adaptation studies along the same lines as Pollack (1952). Effects of continuous as well as intermittent noise were investigated; noise levels were kept constant at 87 and 90 dB SPL respectively for the experimental conditions.

Furthermore, Pollack (1951) studied the effects of contralateral intermittent bandpass noise using the same parameters and methodology as in the afore-mentioned studies. The study showed that there were no changes in loudness as interruptions increased. In contrast, Carterette (1955) attempted to replicate the study by Pollack on the effect of contralateral intermittent bandpass noise on adaptation. The findings of this study showed that as the interruption rate increased, adaptation also increased, thus contradicting previous study. Also, Pollack found that higher interruptions rates than those used in the Carterette study, resulted in reduced loudness.

In an attempt to reconcile his results with those of Pollack, Carterette offered the following explanation: with an increase in the interruption rates, the silent intervals between bursts decrease. As a result of diminished silent intervals there was insufficient time for neural recovery between the succession of bursts, thus causing cumulative adaptation effects.

The clinical and physiological implication of auditory fatigue and adaptation are compelling. Persons with normal hearing and those with cochlear impairment usually reveal slight to mild adaptation. However, patients with involvement of the auditory nerve show abnormal adaptation (Konkle and Orchik, 1979) with the result that auditory adaptation has grown to be a site of lesion test for distinguishing cochlea from retrocochlear lesions.

From the above, it is apparent that auditory adaptation is more relevant to the present study than auditory fatigue. Since this section of the present study is aimed at examining the nature of forward masking, it suffices to point out that Ward (1973) identified four types of adaptation. They are concomitant binaural (perstimulatory adaptation, i.e., during the adaptation process); concomitant monaural (tone decay), residual binaural (loudness reduction and timbre change), and residual monaural (temporary threshold shift).

Effects of Forward Masking on the BAEP

Auditory masking is a decrease in audibility of one sound (the signal or probe tone) in the presence of another sound (the masker).

By introducing the masker while the signal is on, the latter may remain audible, although at a decreased loudness. This phenomenon is called partial masking. Forward masking refers to a situation where the masker precedes the signal. As the present study examines the effects of forward masking on the wave I' potential of the ABR, the focus of the review of literature in this section was confined to forward-masking as a specific technique masking a signal.

Zwislocki (1978) defined forward-masking as the "after-effects" experience during the period that elapses 0.5 seconds after the signal has been turned off. The after-effects are subsumed under the notion of forward masking. Salient variables that are associated with forward masking are the time between the masker and the signal, intensity of the signal and of the masker, the rise/fall time of the masker, and the interstimulus interval (ISI) between the masker and the signal (or probe).

Pioneers in the field of forward masking appeared in the mid-1940s. It was at that time that two groups, lead by Luscher and Munson, were the first investigators to explore the effects of forward masking. Both used the same stimulus paradigm in which a masking sound preceded a short tone burst. The difference between the masked and unmasked thresholds was interpreted as the effects of masking. The method used by these investigators has now become standardized for forward masking experiments.

Experiments on forward masking were traditionally performed with a masking duration of at least 400 ms, which allowed for a steady state response. Both the masker and the signal were presented with a 10 ms rise/fall time so as to prevent audible transients from inter-

fering with an on or off time. The duration of the signal was at least 20 ms. The independent variable of the experiment was time that elapsed between the offset of the masker and the onset of the signal. This interval was called the delay time in pioneering experiments.

Based on the these experimental protocols and the findings by Luscher and Zwislocki (1947), as well as others, the following findings were identified: (a) as the intensity of the masker increases, so does forward masking; (b) forward masking becomes less effective as the delay time between the masker and the increases; (c) higher masker intensity causes more decay than the moderate intensity level. Thus, a 300 ms interval (also known as delta-T) showed no effects of masking; (d) forward masking does not depend on sound frequency, if the sound levels of both the masker and signal are kept constant at the same intensity.

The second group focused on the impact of the frequency distribution on forward masking with emphasis on intensity of the masker (Gardner, 1947; Munson and Gardner, 1950). These investigators identified the following: (a) the masker frequency was maximum at low and moderate intensities; (b) as frequency settings increased toward higher frequencies, there was a gradual decay; and (c) a rapid decay was seen as lower frequencies were selected.

In considering the findings made by Gardner (1947) and Munson and Gardner (1950), Zwislocki and Pirodda (1952) pointed out that the apparent gradual shift toward higher frequencies arose from the secondary maxima of the masker, when a 80 dB SL was exceeded. These investigators argued their case on the basis of testing three subjects with a masker of 3150 Hz and intensities of 60 and 100 dB SPL.

Subsequently, it was realized that the difficulty in understanding the occurrence of forward masking was compounded not only by the frequency interaction that occurred between the masker and the signal tones and the time delay from masker off-set, but also by the masker duration (Zwislocki, Pirodda, & Rubin, 1959). These investigators stated:

> "the poststimulatory threshold is nearly independent of the duration of the test stimulus as long as this stimulus terminates within 150 msec from the end of the prime stimulus. For longer intervals the threshold decreases as the duration of the stimulus increases, due to temporal integration. For shorter time intervals temporal integration is minimized by the rapid change in sensitivity. (Zwislocki et al., 1959, 13)."

Although most experiments were performed with pure tones as maskers, their results proved to be also valid for broad- and narrowband masking.

Elliot (1962) confirmed the findings by Zwislocki and co-workers. It became evident, therefore, that: (a) time delays that were less than 200 ms appeared to result from the time delay of the signal offset; (b) time delays greater than 200 ms caused longer stimuli which resulted in lower threshold than when a short stimulus was used. Zwislocki (1960) had previously identified these findings as the effects of temporal summation. It remained obscure as to why temporal summation did not appear in shorter time intervals. It is, nonetheless, apparent that the slope of the masking function could be

a contributory factor. Furthermore, Zwislocki et al. (1959) showed that forward masking as a function of delta-T did not yield an exponential curve.

Effects of Toneburst and Frequency on the BAEP

Derbyshire and Davis (1935) were the first to describe adaptation in the compound action potentials. However, Hughson and Witting (1934) were the first investigators to show cochlear potential postimulatory reduction, which they believed was due to fatigue. These investigators identified four types of effects on cochlear and auditory nerve potentials (masking, adaptation, fatigue, and recovery).

From the mid-1930s to the 1970s, research on the behavior of the cochlea and the auditory nerve attracted many investigators. In 1938, Stevens and Davis identified the key problematic issues revolving around masking, fatigue, and recovery period. Following are some of the factors pointed out by these investigators: (a) lack of agreement among reseachers on these topics; (b) fatigue as measured by the recovery period depended on the frequency of the masker; (c) there was significant subject variability in recovery from stimulation, under identical conditions; (d) in examining the ways fatigue was measured there seemed to be some effects on the auditory system that originate from the CNS which could not be determined through psychophysical techniques. Intensive research in the fields of masking and adaptation developed in the 1950s and grew for more than the next three decades. Main points that surfaced

during this period are highlighted in the following paragraphs of this section.

Davis, Morgan, Hawkins, Galambos, and Smith (1950) found that a threshold was reach when stimulus intensities were increased from 110-130 dB SPL. Their results also revealed that as the duration of stimulation increased, from 1 to 64 minutes, the auditory threshold shifted, implicating the occurrence of auditory adaptation and/or fatigue. Studying poststimulatory effects in the cochlea, Hood (1950) found that an increase of stimulus intensity between 60 and 90 dB SPL resulted in a minimal increase in threshold. Significant changes in threshold emerged at equal or higher than 90 dB SPL level.

Jerger (1956) found that 90 dB of stimulation was a critical intensity level. Furthermore, he reported that as intensity level increased beyond the critical point, recovery time increased considerably. These findings revealed a consistent pattern with the one suitable for the process of fatigue. Masking process was also closely examined by several investigators. Some interpreted this phenomenon as a asynchrony that arises during neural excitation (Peak, Kiang, & Goldstein, 1962), while others described it as a "line-busy" effect (Teas, Eldredge, & Davis, 1962; Kiang, Watanabe, Thomas & Clark, 1965). Those who called it the "line-busy" effect did so because during masking, the masker (which could be tone or noise) activates nerve fibers making it difficult for them to respond to the signal that follows after delta-T. That is, fibers are momentarily in a refractory state and, therefore, cannot respond to acoustic stimuli, regardless of the level of intensity.

In addition, research of single nerve fibers indicated that masking tended to impede the total rate of firing. This observation was not made when the masking noise was absent. It was postulated that the "line-busy" effect, as well as reduced firing rates that were observed during masking, was related with adaptation.

Coats (1964a, 1964b, 1967, 1971) made several investigations using the forward masking paradigm on the behavior of the cochlea. He, nonetheless, focused on conditions where delta-t was longer than 10 ms. He concurred with the notion of the "line-busy" effect. In addition, Coats found that the recovery time was longer than the refractory period.

Studying the relationship between masking and adaptation for intracochlear recorded CAPs, Spoor (1965) reported that masking of the AP was maximal in unadapted situations. This investigator explained that at a given increment of intensity level of the masker, the amplitude decreased at a relatively accelerated rate in unadapted conditions rather than in situations where the ISI was reduced. From this study at least two points could be made, namely: (a) the nature of masking and adaptation; (b) that properties of masking and adaptation are identical. Subsequently, Eggermont and Spoor (1973b) pointed out that the "line-busy" effect resulted possibly from adaptation.

Investigating dimensions of cochlear acoustic stimulation, Teas and Henry (1969) considered the effects of masking and the rates which were most effective. Kupperman (1971) analyzed, among other features, the relationship between masking and the presence of a positive SP. This investigator concluded that SP was optimal where the masker elicited maximal excitation in the cochlea. In addition,

upon investigating location for pure tones at various intensities as continuous stimuli were presented, as well as forward masking, Spoor and Eggermont (1971) found that the main difference between continuous and forward masking, where small time delays were used, was the effective masking level.

Eggermont and Spoor (1973a, 1973b) investigated the effects of masking and adaptation of N1 on 18 guinea pigs. Included in their forward masking paradigm were short stimulus tones (signals) which were ideal for the on-effect. On the other hand, the masker had long durations which were suitable for studying the influence of masking on the signal (Coats, 1964a).

In both studies made by Eggermont and Spoor, the following stimulus paradigms was employed: (a) noise (masker) with a plateau of 500 ms and a rise/fall time of 2 ms; (b) signal (tone stimulus) had a plateau of 1 ms and a 0.33 rise/fall time; (c) the tone frequency was 6 Stimulus intensity was 50 dB SPL; and (d) repetition rate used in study was 1 stimulus per second.

These experiments revealed the following pattern: (a) after a delta-t of 1 ms, recovery began to occur regardless of the magnitude of the S/N ratio; (b) the unmasked amplitude of N1 is reached after a delta-t of 250 ms; (c) N1 amplitude appeared to be dependent on the S/N ratio, in contrast recovery time remained unchanged for different S/N ratios; (d) a decrease in the S/N ratio resulted in a decreased amplitude, while latency increased; (e) at short delta-T values, there was a significant S/N ratio that was dependent on the plateau; (f) at equal or less than 0.08 ms different S/N ratios (20, 10, 0, and -10 dB) showed variation, and (g) an asymptote for N1

amplitude was reached at delta-t of 64 ms (instead of delta-T of 250 ms).

It is obvious that the behavior of the auditory system in response to acoustic stimulation, when different stimulus parameters (i.e., intensity, frequency, and time) are manipulated, is extremely complex. Examination of the effects of forward masking cannot be fully appreciated without considering the effects of adaptation, fatigue, and neural recovery during masking. Furthermore, is apparent that even changes in auditory sensitivity, often observed in subjective thresholds, may not be entirely explained in terms of auditory fatigue and adaptation since the nature and degree of inhibition contributed by the CNS remains as unknown today as it was more than thirty years ago (Gisselsson & Sorensen, 1959).

Eggermont and Spoor (1973b) studied the effects of masking on AP in the guinea pig. They found that the amplitude and latency of N1 were affected by noise in the forward-masking paradigm. In addition, there were different response patterns when white noise was presented below and above 60 dB. They also found that adaptation competed with masking in the presence of noise (masker). Furthermore, the investigators observed that when stimulus intensities were equal to the S/N ratio and interstimulus interval (ISI) maintain the correlation.

In different experimental conditions, the investigators examined the effects of forward masking on compound action potential. They found that forward masking was more effective when the delay time was minimal. Further, they subdivided the period of maximal effectiveness into three parts, namely: (a) a period of long delays which was influenced by refractory mechanisms; (b) a period of long delays in

which adaptive mechanism depended solely on masking, and (c) a middle period which was characterized by a combination of both refractory and adaptive mechanism.

It is apparent that investigations on the behavior of the VIIIth nerve in the mid-1960s were in essence the reflection of Derbyshire and Davis (1935). Using modern instrumentation the term "auditory nerve neurophonic" (ANN) was invented to refer to neural responses that are minimally affected by CM at stimulus intensities lower than 80 dB SPL. Tsuchitani and Boudreau were the first to introduce this term (Tsuchitani and Boudreau, 1964; Boudreau, 1965a, 1965b). Thus, these investigators elaborated on the germinal work that had been considered about 30 years before. To date, the notion of ANN remains an unexhausted field of research.

In order to gain an insight into the nature of the ANN, a brief comparison between this phenomenon and the CM is in order. The most notable characteristics between the events are: (a) CM tends to be a close replication of the original stimulus, while ANN does not; (b) CM has no latency whereas ANN does (depending on stimulus intensity level); (c) CMs have been found to occur even after an organism had expired; and (d) whereas CMs are of a non-neural nature that are confined to the cochlea, ANN are neural in origin. Further, auditory neurophonics (ANs) have been found in various auditory nuclei [e.g., trapezoid body, superior olivary complex (SOC), the lateral lemnicus (LL)].

Weinberger, Kitzes, and Goodman (1970) found ANs in SOC (in both lateral and medial aspects), LLs, and inferior colliculi (IC). Stimulus intensities were presented at levels between 80 and 90 dB

(re 0.0002 dynes/cm^2). For instance, ANs at this range of intensity level, emerged at latencies of 2 and 3.5 ms, for trapezoid body and IC respectively.

In a forward masking paradigm, Snyder and Schreiner (1985) examined the occurrence of the ANN as well as the frequency following response (FFR) in 45 otologically-healthy adult cats. For stimulus protocols, the investigators used high (1,800 Hz), medium (1,400 Hz), and low (600 Hz) masker frequencies which preceded the 800 Hz signal (i.e., the probe tone of 20 ms, with 5 ms rise/fall time) for eliciting ANNs. The maskers were presented at the stimulus intensity levels between 30 and 90 dB SPL at 10 dB steps, while the signal was constant at 50 dB SPL. Similar experimental protocols were used for eliciting FFRs; the only differences were the use of 600, 1,600, and 2,400 Hz as maskers. Their results were similar to those of Weinberger et al., (1970).

In general, the forward-masking behavioral patterns of the ANNs and FFRs were very similar. Detailed analysis of the ANNs revealed the following trends: (a) high-frequency tone masker (1,800 Hz) seemed to have minimal effects on the signals, even when the masker was set at maximal intensity levels; (b) mid-frequency tone masker (1,400 Hz) appeared to elicit suppression of responses at levels below 30 dB SPL; and (c) low-frequency masking (600 kHz) resulted in a strong decrease of the signal response at 50 dB SPL and higher. In addition, these investigators indicated from their forward-masking tuning curve data that the degree of the neurophonic suppression was a function of both intensity level and the frequency masker. This condition also held for the neurophonic recovery times. In addition,

it was shown that when maskers with low levels preceded a low intensity signal, the ANN is not masked, but enhanced.

Weinberger and co-workers (1970) found auditory neurophonics in the trapezoid body, superior olivary complex (in both the lateral and the medial aspects), the lateral lemnisci, and the inferior colliculi. Stimulus intensities were presented at levels between 80 and 90 dB (re 0.0002 dynes/cm^2). For instance, auditory neurophonics (AN) at this intensity range emerged at the latencies of 2 and 3.5 ms for the trapezoid body and inferior colliculus, respectively.

In a forward masking paradigm, Snyder and Schreiner (1985) examined the occurrence of the ANN as well as the frequency following responses (FFRs) in 45 otologically-healthy adult cats. Experimental conditions employed were similar to those mentioned in the Weinberger et al. (1969) study. These investigators employed high (1,800 Hz), mid- (1,400 Hz) and low (600 Hz) masker frequencies which preceded the 8,000 Hz signal (probe tone of 20 ms duration, 5 ms rise/fall) for eliciting ANNs. The maskers were presented at the stimulus intensity levels between 30 and 90 dB SPL at 10 dB steps, while the signal was constant at 50 dB SPL. In order to elicit FFRs, similar experimental protocols were used. The only difference was that 600, 1,600 and 2,400 Hz masker frequencies were used.

In general, forward-masking behavioral patterns of the ANN and the FFR appeared to be similar. Trends of the ANN responses may be summarized as following: (a) high frequency (1,800 Hz) seemed to have minimal effect on the signals, even when the masker was set at maximal intensity levels; (b) mid-frequency (1,400 Hz) masker appeared to elicit suppression of responses levels below 30 dB SPL; (c) low

frequency (600 Hz) masking resulted in a strong decrease of the signal response at 50 dB SPL and higher.

Similar to the previously reported studies, these investigators found that their forward masking tuning curves together with their recovery times, occurred as a function of both intensity level and the frequency of the masker. Also, it was shown that when maskers with low levels preceded a low level signal, the ANN was not masked but enhanced.

Forward masking of the auditory nerve response was defined a "a reduction in the magnitude of the probe-evoked response caused by addition of the masking stimulus" (Harris & Dallos, 1979, p. 1083). In studying the auditory nerve responses as a function of forward masking these investigators made the following observations: (a) signal (probe) response magnitude, as a function of delta-T, in forward masking tended to recover in an exponential trend; (b) forward masking tuning curves, at or near thresholds, resembled the frequency threshold curves; (c) outside the borders of the fiber's frequency threshold curves, two-tone suppression had no forward masking effects; (d) duration pattern and the size of the forward masking impact depended on the rate of discharge affected by the maskers. Thus, increase in intensity of the masker resulted in reduced magnitude of the signal response. Parallelism between the masker and the signal response, in terms of the firing rate held up to 40 dB SL (re-signal threshold); (e) signal response magnitude, as well as the time constant of recovery decreased as a function of the masker duration. No observable difference occurred between the 100 and 200 ms time range of masking; and (f) the period of poststimulus

recovery, followed when single fibers were exposed to forward masking. It was thought that this could be the time of recovery from adaptation.

Recent studies on forward masking focussed on the ABR part of the central nervous system, particularly wave V. Ananthanarayan and Gerken (1983) studied poststimulatory effects in human ABRs using delta-T of 5, 15, 45, and 135 ms in forward masking conditions. A 10 ms tone was preceded by a 60 ms noise masker with 10 ms rise/fall time. These stimuli were generated and run through the Grass amplifier with 100 dB gain and 100-3,000 Hz bandpass. Every ABR was gathered from 1,500 stimuli representations that had been averaged with a 34.78 microsecond dwell time and 1,000 points. The findings of these experiments showed that: (a) waves III and V behaved in a similar way, in terms of latency and delta-T functions. Simultaneous delta-t of 5 and 15 ms conditions produced significant latency shifts for wave V. Similarly, greater amplitudes for wave V were observed when delta-ts were 5, 15, and 45 ms. Maximal latency shifts for both waves III and V occurred in the simultaneous condition; (b) amplitude of wave III, as function of delta-T, which appeared to be a response to partial masking, showed significant reductions. In comparison with wave V, amplitudes for wave III, when delta-T was 5, 15, and 45 ms, resulted in more diminished amplitudes than in the unmasked experimental conditions; (c) wave V amplitude showed maximal enhancement when delta-T was 15 and 45 ms; and (d) even when delta-T was 135 ms, waves III and V latencies did not return to unmasked latencies.

Subsequently, Ananthanarayan and Gerken (1987) studied the effects of different forward masking stimulus parameters on

amplitude. Experimental parameters included in their studies were: the frequency of the masker, the relative level of the masker, the masker rise/fall time, as well as, intensity levels of the masker and the signal. Based on the data collected from 15 normal-hearing young adult human subjects, the following findings were made: (a) the masker frequency effects: (1) masker frequency produced different effects on amplitude and latency magnitudes in waves III and wave V. While the maximal latency occurred at about 4,300 Hz for wave III, wave V maximal latency emerged in the vicinity of 3,750 Hz; (2) In both waves, frequency makers that were proximal to the signal resulted in larger latency shifts than those that were remote from the maskers; (3) In most subjects wave III had higher amplitude reductions for equal or fewer than 4,000 Hz than for higher than 4,000 Hz masker frequencies; (4) wave V showed a frequency-dependent pattern of enhancement; (5) analysis of variance test of waves III and V revealed significant latency shifts ($p < 0.0003$) as well as amplitude changes ($p < 0.0002$). (b) the effects of relative level of masking: (1) as the masker intensity level increased, waves III and V latency increased (that is, parallel latency shifts occurred); (2) wave III displayed a decrease in amplitude as the masker level increased; (3) wave V amplitude was enhanced at all masking levels; (4) for unmasked experimental condition both latency and amplitude showed significant changes ($p < 0.0005$). (c) the effects of the masker rise/fall time: (1) wave III amplitude reduced in masked conditions, while wave V was enhanced, reaching maximal level at 10 ms rise/fall time condition; (2) waves III and V latencies decreased as the rise/fall time increased (from 0.05 to 10 ms). Wave III latency decrease

exceeded wave V at 10 ms rise/fall time; (d) the effects of three masker-probe pairs intensity levels (45, 55, and 65 dB SL): (1) wave V amplitudes remained definable in the three conditions. More amplitude enhancement occurred at 55 and 65 dB SL than at 45 dB SL; (2) wave III was hard to identify at 45 dB SL. It was observed in only a few subjects; (3) waves III and V latency shifts, as a function of masker-probe intensity level, were basically parallel to each other with the minimal latency increases as the signal and masker levels were jointly increased.

Effects of Frequency on the BAEP

Frequency Specific Responses:

According to Harris and Dallos (1979), the notion of frequency selectivity first surfaced in 1876 when Mayer performed his psychophysical investigations. However, it was not until 1924 that Wegel and Lane (1924) first quantified frequency selective properties of the auditory system. Using the tone-on-tone masking paradigm, these investigators observed frequency specific patterns on the basis of masking curves. Subsequently, more definite frequency-dependent psychophysical tuning curves (PTCs) were recorded in human subjects (Finck, 1966; Moore, 1978; Small, 1959) as well as mammals such as the chinchilla (McGee, Ryan, & Dallos, 1976). The PTCs obtained by different researchers were corroborated by the frequency threshold curves (FTCs) recorded from single auditory fibers.

Bauch Rose, and Harner (1980) investigated the effects of tone pips and click stimuli on ABRs in normal-hearing adults. Their tone

pip responses were elicited with 1,000, 2,000, and 4,000 Hz stimulus frequencies with the total overall duration of 4 ms (2 ms for the plateau and 1 rise/fall time) and the clicks of 50 micro-seconds. All stimuli were delivered at the rate of 30 per sec through the Bruel and Kjaer condenser microphone (4134) embedded within the TDH-49 earphone.

The procedures employed by these investigators included intensity series in which data was collected at 80, 60, 40, 30, 20, 15, 10, 5, and 0 dB HL (re: their norms). Replication of responses was made for stimuli presented below 30 dB HL.

Results of this study revealed the following findings: (a) auditory sensitivity was clearly reflected by the wave V; (b) there was an inverse relationship between wave V latency and intensity as well as between wave V latency and stimulus frequency of tone pips. Dispersion of responses around wave V for 1000 and 4000 Hz tone pips showed a significant overlap; and (c) waves II, III, and IV were hard to identify at low intensities.

Examining the effects of frequency on latency within a subject, Moore (1983) used the following experimental conditions: (a) data was collected from a 23 year-old normal-hearing female human subject with vertical montage electrode placement (Cz - M2); (b) five short tone bursts were administered to the ipsilateral ear (500, 1,000, 2,000, 4,000, and 8,000 Hz) with 1 ms rise/fall time and 3 ms duration (with 5 ms overall duration); (c) repetition rates of 10.21 stimuli per second were used and 1,024 sweeps were averaged; and (d) attentuation of latencies varied from -40 dB to -10 dB.

Based on Moore's data, the following findings became apparent: (a) in terms of waves III and V, there were no differences across

frequencies which could be attributed to frequencies used in the experiment. There was an indication, however, that wave I was generated more by the basal than apical cochlea, as seen in the resultant shorter latencies and more amplified amplitudes; (b) wave I latencies differed from one frequency to another as a function of low stimulus intensity. There seemed to be no differences at high stimulus intensity.

Subsequently, Kodera, Marsh, Suzuki, and Suzuki, (1983) investigated the contribution of tone pips to frequency-selective ABRs. To achieve objectives of their study the investigators varied their rise/fall times while the gradient is kept constant. They studied six normally-hearing cats in their experiments. Stimulus parameters used in the study comprised tone-pips with linear onset and offset slopes of 0.5, 1, 2, 4, and 8 ms. There was no plateau between onset and offset ramps. Tone pips were presented at interstimulus intensities ranging from 34 to 88 dB pe SPL and speech frequencies (i.e. 500, 1,000, and 2,000 Hz). Further, alternating stimulus polarity was used to prevent occurrence of electrical artifacts. Recordings were made differentially between the midline scalp and the bulla ipsilaterally, while the third electrode was grounded on the contral-lateral bulla.

Results of this study revealed the following pattern: (a) 2,000 Hz tone pip had more than 2 ms range of effectiveness; (b) longer rise/fall time appeared to be related to reduced amplitudes with the same intensity level; (c) distinct patterns of increasing ABR latencies were found at all levels where the rise time was higher than 4 ms.

In a similar study made by Dolan and Klein (1987) on gerbils, it

was found that a decrease in the length of the rise/ fall time from 2.0 to 0.75 ms resulted in a marked displacement of the 8000 Hz tip in the whole-nerve action potential tuning curves. These results are suggestive of the notion that shorter rise time tend to produce increased off-frequency response.

In general studies on frequency selectivity supported the view that there is an inverse relationship between the stimulus frequencies selected and the output latencies (Suzuki, et al, 1977). Furthermore, N_1 amplitude increased in response to the third octave clicks to 500, 2000, and 8000 Hz (Naunton and Zerlin, 1976). However, complexity arises from the multiple interaction of different stimulus parameters that occur simultaneously. For instance, Suzuki and his co-workers (1977) did not find decreased detectability to responses when the 500 Hz stimulus was presented to their subjects. Their findings were a contradiction to the results found in previous studies (Suziki and Horiuchi, 1977, Elberling, 1976, Davis and Hirsh, 1976). From these studies it was apparent that the use of high pass filter contributed in reduction and distortion of responses to the 500 Hz tone pip.

Effects of Urban life on Auditory and Nervous Systems

There is evidence to the effect that the urban lifestyle has a significant influence on urbanites. Populations in the low socio-economic bracket in inner-cities are often negatively affected by their environment. The label 'poverty' seems to be the blanket term embracing major factors that impoverish urban health conditions in

depressed areas. Furthermore, urban problems such as high crime rate, homelessness, poor housing of residents, poor nutrition, high unemployment rates, low literacy level, and inadequate health care are typical features of a capitalist system that requires unequal distribution of wealth for its survival. Infant mortality rate as well as the populations' life span are commonly very strong indicators of the city or nation's level of advancement. Studies reviewed in this chapter are confined to health services.

Incidence of teenage and adolescent pregnancy is one of the main problematic features in the inner-cities. Studies have consistently shown that teenagers from low socio-economic brackets in the inner-cities tend to have higher pregnancy rates than teenagers from the middle and upper classes. According to Allen (1980) and Franklin (1987) black teenagers have continuously been found to have higher pregnancy rates than their white counter-parts. Thus, there are generally more children at-risk among black teenage mothers than among white teenage mothers. Children on the at-risk register have a high prevalence of neurologic disorders.

Illegal drug ingestion occurs frequently in urban areas among the low income communities. Pregnant mothers have been reported to take drugs such as alcohol, narcotic agents, marihuana, tobacco, etc., which had adverse effects on the unborn fetus or reproductive organs. Handicapped children and adults have been found to display fetal alcohol syndrome (FAS) to a higher degree than those with fetal alcohol effects (FAE) (Jones & Smith, 1973a). These patients were born to chronic alcohol mothers (Jones & Smith, 1973b, Asante, (988). According to Ostrea: "Almost all of the narcotic drugs ingested by

the female addict during pregnancy cross the placenta and enter the fetal circulation" p. 23. Upon inhaling cigarette smoke, 14 to 41 ng/ml of nicotine in dissolved into the blood stream (Gennser, Marsal, & Brantmark, 1975; Manning & Feyerabend, 1976). Through the circulatory system and body fluids nicotine is to transported to the CNS, particularly, the brain, the pituitary, and the adrenal (Tsujimoto, Tanino, Dohi, & Kurogochi, 1975) which has detrimental effects to the fetus.

Summary

Chapter II reviewed literature that is relevant to wave I′ of the brain-stem auditory evoked response (BAEP). Three broad topics have been employed to achieve the objective of the chapter: history of wave I′ of the BAEP; physiological and psycho-physical environment where the wave I′ frequently occurs; and stimulus-parameters which were used to elicit wave I′ were described.

History of Wave I′ of the BAEP

The notion of wave I′ in humans first surfaced in the early 1980s when three groups of investigators (Hughes & Fino, 1980; Benito et al, 1984; and Moore and Semela, 1985) independently observed this phenomenon. After using several names for identifying this potential, Moore and Semela adopted the term coined by Hughes and Fino.

Physiological, and Psycho-Physical Environment of Wave I′

Two classes of connecting potentials were considered in this chapter. They are synaptic and coupling potentials. Pujol and Lenoir (1986) considered four types of synapses. They are: (a) auditory

dendrites--found between IHCs and radial afferent fibers; (b) axo-dendritic synapses which are located between the lateral efferent endings and the auditory dendrites; (c) synapses between the OHCs and the spiral efferent fibers; and (d) axosomatic synapses between medial afferent endings and OHCs. Competence of the auditory system is dependent upon the integrity of the synapses.

Coupling potentials are acoustic stimulus-related responses that appear when hair cell stereocilia are displaced. As a result of acoustic stimulation hair cells, basilar, and tectorial membranes are set in motion so that acoustic transduction occurs. How coupling actually occurs remains uncertain.

The excitatory and inhibitory nature of the auditory neural pathway was explained in terms of the excitatory and inhibitory postsynaptic potentials. The functional nature of synapses has been characterized by two features, the valve action and the synaptic potentiation. The former refers to the provision of gaps along the CNS which facilitates competence of the system. The latter on the other hand, refers to an increased number of synapses within a fiber track which improves the efficacy of synaptic potentials.

Effects of different parameters on ABR were reviewed. These included filters, polarity, repetition rate, forward masking, adaptation, fatigue, and frequency. The effects of these parameters on the auditory responses were considered along the major features--latency, amplitude, and morphology. Urban condition was reviewed in terms of the impact poverty may produce in human life. Emphasis was placed on the effects of low socio-economic status on teenagers, and drug ingestion on teenage mothers.

CHAPTER III

BASIC INSTRUMENTATION AND METHODOLOGY

The following hypotheses were formulated for the present investigation

Null-hypotheses

(1) Wave I′ is a non-neural potential which precedes wave I of the BAEP;

(2) Wave I′ of the BAEP is a transient summating potential of the cochlea that develops from the electrical dc shift.

Hypothesis

Wave I′ of the BAEP is a neural cochlea potential.

In order to test these hypotheses, the following procedures were employed: subject selection, subject preparation, instrumentation, and electrophysiologic neural adaptation tests.

Subject Selection Procedures

Subject Selection Criteria

A random sample of normal-hearing human subjects was selected from the population to participate in the investigation. In order to

determine whether subjects exhibited normal hearing, the following were explored for each individual.

Case History: Subjects provided past and present history on the status of their hearing and their medical and family history of hearing-related disorders. Information such as head trauma, chronic middle ear involvement, long durations of exposure to suprathreshold noise and long-term drug use were considered. Subjects were requested to complete in Adult Case History form shown on Appendix C.

Otoscopy: This test was administered to rule out the following possible conditions that have been found to influence BAEP test results: (a) unusually small pinnae (e.g. microtia) and external auditory meati; malformation, displacement or absence of the pinnae; (b) excessive cerumen in the external auditory meati; and (c) abnormal conditions of the eardrum.

In addition to otoscopy, the circumference of each subject's head, in relation to the size and shape of the pinna was noted. The importance and relevance of this observation is that there is a strong correlation between the pinna and the ossicular chain. These structures have a common origin in the first and second branchial arches during the fetal stage of development. Thus, pinna malformation may be indicative of middle ear disorders (Finitzo-Hieber, Hecox, & Cone, 1979).

Tympanometry and Impedance: All subjects had tympanometric as well as impedance assessment prior to participation. Normal type A tympanograms were first determined for individual subjects.

Pure Tone Audiometric Evaluation: To ensure normal, behavioral test results, pure tone hearing thresholds from 250 Hz to 8,000 Hz were determined for each subject (Beltone Audiometer 112).

Age: An age range of twenty to forty years with a mean age of 26.82 years was selected. Selection of this age group was found to be representative of the population age in the middle of the life span. Subjects were drawn from a multi-cultural, university population.

Gender: Subjects in this study included only females, as it has been shown that females tend to have shorter latencies and larger ABR amplitudes than males (Jerger & Hall, 1980; Kjaer, 1979; Allison, Wood, & Goff, 1983; Michalewski, Thompson, Patterson, Bowman, & Litzelman, 1980; Stockard et al, 1978; Beagley & Sheldrake, 1978). This eliminated sex variation and thus increased statistical power in the study.

Subject Release Forms: Prior to participation in the investigation subjects were given a full explanation as to the nature and objectives of the investigation. Those subjects who were willing to participate in the investigation under the given conditions were required to sign consent forms shown in Appendix D.

Subject Preparation and Electrode Placement Procedures

The aim of these procedures was to obtain maximal bio-electrical contact between the subject and the BAEP measuring instrumentation, as well as to create a comfortable and relaxing environments for subjects during testing.

Subject Preparation: For surface recordings, the electrode contact points were cleaned with alcohol and omni-prep, a chloride and acetone free abrasive paste. For intra-tympanic recordings, a custom solution (3 percent hydrogen peroxide diluted in water and 70 percent Ethyl Lavacol alcohol) was used to irrigate the external auditory meatus via a 3cc syringe. For subjects that exhibited a sensitive external auditory meatus, xylocaine was applied as both an anesthesia and a cleansing agent.

Electrode Selection: For surface electrophysiologic data collection, Grass E5GH Gold Plated Cup Electrodes were used. Gold electrodes were selected because of their durability and capacity to reduce interference from electrode polarization (Coats, 1983). Electrode paste was filled in the cup electrodes; and applied to the skin by means of surgical tape (3M Micropore). The hole in each cup electrode enabled the investigator to insert a blunt needle to gently abrade the skin and reduce electrode impedances.

Electrode Placement: Placement of surface electrodes was done in accordance with the International 10/20 Electrode Placement System (Jasper, 1958) as shown in Appendix E. A vertical montage electrode placement was used in the present study; data were collected between Cz-A2 or Cz-A1, and the ground electrode was placed at the forehead (Fpz).

Electrode Impedance: An electrode impedance meter (Grass Model EZM 5) was used to measure intra-electrode impedance, and all exhibited impedances less than 2.0 kOhms.

Intra-tympanic Electrode Placement and Impedances: Prior to the placement of this electrode, conductivity gel (Meditrace) was mounted onto the Coat's Leaf eartrode. The investigator used forceps (Brownie) for placing the electrode in the external auditory meatus, with the ball of the electrode oriented on the inferior part of the ear canal. Impedances of this electrode were within the range of 25 kOhms.

INSTRUMENTATION

The central data collection and processing units used in this study were a microcomputer (IBM PC AT) coupled to a digital stimulus generating system (Modular Instruments Inc.). Together these instruments had the capacity of generating acoustic stimuli and averaging and processing the responses detected from subjects. Figure III-1 is a schematic of equipment used in this investigation. Figure III-2 is an illustration of the different experimental conditions employed in the present investigation. The Signal Averaging (SA) and the Signal Processing (SP_1) programs were employed for collection and display of waveforms. A brief explanation of these programs follows.

The Signal Averaging Program (SA)

Underlying the SA process is the principle of elimination of ongoing background noise by increasing the signal-to-noise ratio. This program, like various other computer averaging techniques, may be viewed in four classes: stimulus, low level analog, digital, and display sections (Appendix F).

Figure III-1. Block diagram of experimental apparatus used throughout the investigation.

Figure III-1

INSTRUMENTATION

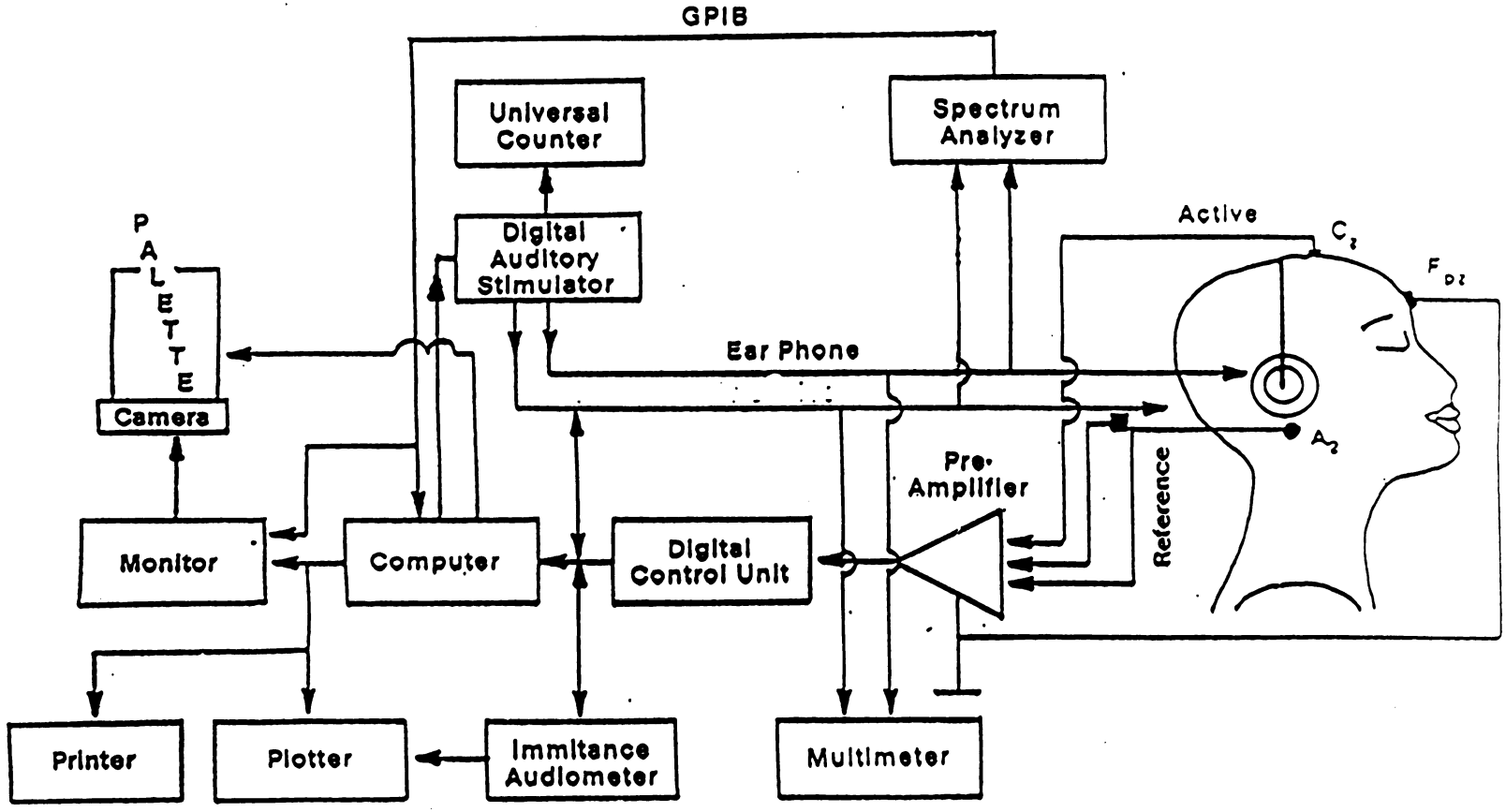
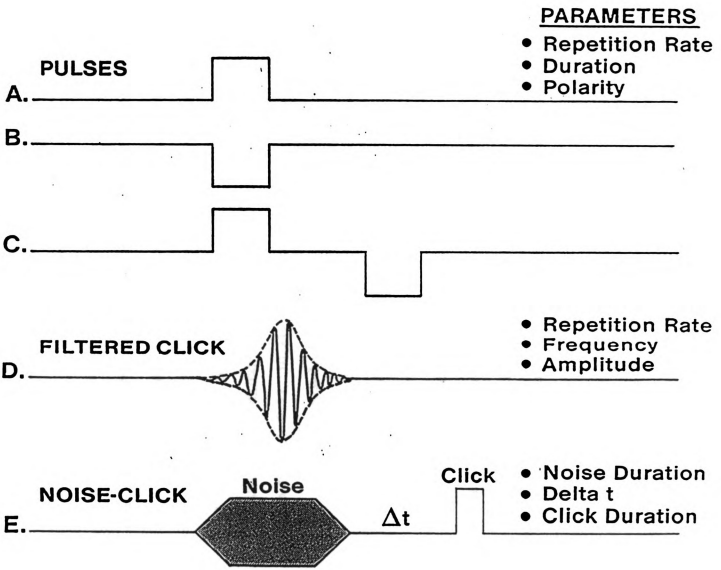


Figure III-2. Block diagram of experimental apparatus used in the five experiments and different conditions in the investigation.

Pulses A, B, and C show three phase conditions used for experiments I, III, and V. Filtered Click D is an illustration of toneburst used in experiment II. Noise-click in E shows a forward-masking paradigm.

FIGURE III-2


PARAMETERS
• Repetition Rate
• Duration
• Polarity
PULSES
A.
B.
C.
FILTERED CLICK
D.
• Repetition Rate
• Frequency
• Amplitude
NOISE-CLICK
Noise
Click
Δt
E.
• Noise Duration
• Delta t
• Click Duration

Instrumentation used in the present investigation appears in figure III-1. The function of each individual component in data gathering may be described in terms of the four sections as follows (Coats, 1983).

Stimulus Section

This section discusses stimulus generation and how acoustic signals are delivered to the ear. Stimulus generation entails parameters such as repetition rate, intensity, polarity, and duration. Furthermore, the need for efficient attenuation and transduction systems received a high priority.

Stimulus Generation: Three stimulus repetition rates were used in the study: 3.22, 10.21, and 96 stimuli per second. There are two reasons for the selection of these repetition rates. First, they are non-multiples of 60 Hz, and therefore assist in improving the signal-to-noise ratio. Second, low and high repetition rates were used in order to "force" the auditory system out of equilibrium (Eisenberg, 1965). Jewett and Williston (1971) stated that, as the stimulus repetition rate increased (e.g., from 2.5 to 50 stimuli per second), the evoked potential waveforms became distorted. Subsequent studies have shown that as the stimulus repetition rate increases, latencies of the waveforms increased, while the N1-N5 amplitude of BAEP waves decreased (Pratt & Sohmer, 1976; Zollner et al., 1976).

Stimulus Duration: The stimulus duration used in this investigation was 0.2 ms. Studies on sound generation have shown that a duration of approximately 0.18 to 0.2 ms produces a maximal sound pressure level (SPL) for short duration stimuli (Durrant, 1983). Furthermore,

the stimuli of choice in this case were clicks since they exhibited an instantaneous zero rise/fall time, a situation which is more ideal for evoking transient responses at the periphery of the auditory system (Eggermont & Don, 1982, 1980).

The second experiment in this investigation examined the filter effects on wave I'. To achieve this goal, morphological patterns of the BAEP were analyzed. Five milliseconds analysis time was employed in an effort to amplify wave I'. Thus, objectives of the experiment are to qualitatively and conventionally evaluate the potential of interest.

In the third experiment, the effects of toneburst stimuli on compound action potential (CAP) were investigated. While the duration of the signal was 4.0 ms, there was no plateau time and thus a rise/fall time of 2.0 ms was employed.

The fourth experiment in this investigation employed the forward-masking paradigm. A duration of 1,000 ms interstimulus interval (ISI) was used. Each interval included latencies of the masker (narrowband noise), the signal (click), and the time separating the masker from the signal (delta-t). Delta-t served as the independent variable in this experiment.

Stimulus Polarity: Using a custom-written computer program, the investigator selected polarity as well as repetition rates in the investigation. The parameters in the present study are described in the following sections. In addition, the investigator could choose to delay the onset of the stimuli in relation to the onset of the sweep, a technique which is useful for avoiding artifact contamination

at the onset of the stimulus.

The Dual Function Generator (M 208): This component resides in the in the MI^2 unit of the microcomputer. It generated stimuli which were transmitted to the transducer (i.e., the shielded Madsen Electronic headphones). Stimulus intensity could be selected within the range of 23 to 116 P.E. dB SPL.

Low Level Analog Section

Two types of pre-amplifiers were used, namely, the Data Inc. (2124 model, 2) and the Grass RPS 107 (Model P511K). Their gains were 1.8×10^5 and 2×10^5 respectively.

Response Amplification: There were three channels through which scalp responses were presented to preamplifier, namely, the noninverting, the inverting, and the common input. These channels execute the following functions. The Cz, or positive electrode position (i.e., the vertex electrode), lead to the non-inverting input of the pre-amplifier. This electrode produces waveforms that peak in the positive direction. The earlobe (A1 or A2) or negative electrode was routed to the inverting part of the pre-amplifier. The product of this channel is a wave that points in the negative direction. The common input combines the results of the non-inverting and the inverting inputs. This combination occurs through the ground electrode, which is placed on the forehead (Fpz) in this study. The differential amplification processes described above, are graphically represented in Appendix G.

Gain and Filtering Effects: The responses are amplified with a gain of 1.8×10^5, which is equivalent to 105 dB SPL. These signal responses are channeled through a bandpass filter with the settings 100 Hz through 3,000 Hz.

Digital Section

In this section four functions of the response recording system are described. First, the digital section converts signals from an analog to a digital form, which enables the computer to recognize and process the data. Second, data is averaged in conjunction with the timer. Third, data that has been processed is stored so that it may be retrieved at a later stage. Fourth, the digital section converts digitized data to analog form. The processed data are transferred to the display section after being translated by the D-A converter.

In the present study the four functions were executed via the combination of the Modular Instruments Inc computer system and the IBM AT units. Through the Data Timer Controller (M 214), a pulse was initiated. This occurred in such a way that it was phase-locked to the click stimuli. Thus, A-D conversion resulted in the generation of binary digital numbers.

Two main features of the A-D conversion had to do with the output resolution, which consisted of time and amplitude. As the sampling rate increased, the time resolution decreased. For maximal amplitude resolution attainment, signal amplitude was set within the A-D converter's amplitude limits. Lastly, the signals were stored in memory after they had been averaged.

Display Section:

Equipment in the present investigation was configured on that data processed could be displayed in nine different ways. These occurred via both auditory and visual modes of presentation.

Auditory Monitors: Two speakers which executed different functions were a part of the system. The first speaker enabled the experimeter to monitor the repetition rate of the stimulus. The second speaker was used to monitor the electroencephalographic (EEG) activity of each subject.

Visual Monitors: The remaining seven channels were displayed visually. The Universal Counter (Hewlett Packard 5314A) displayed the rate at which stimuli were presented to the earphone. The repetition rate displayed by this unit was generated by the Dual Function Generator (M208) within the Modular Instruments Inc. The investigator matched the readings of the universal counter and those of the input in the Dacpulse program within the computer. The Digital Multimeter (Hewlett Packard model 3466A) provided feedback on the level of intensity from the Dual Attenuator of the Modular Instruments (M 108).

Through the output displayed on the oscilloscope (Tektronix D15) it was possible to observe four tracings. The first tracing represented the stimulus delivered to the subject's ear. This tracing confirmed the type of stimulus polarity selected and the amplitude of the stimulus; it also corresponded with the universal counter readings. The second tracing monitored the output of the trigger pulse. It confirmed that the trigger delay at the output corresponded with the

input setting. The third tracing represented the output from the power amplifier. It confirmed that the signals transmitted to the earphone were identical to the ones presented at the input. The fourth tracing was a reflection of the subject's EEG activity. This tracing enabled the experimenter to visualize physiologic activities that were also heard via the speaker as described previously.

The camera monitor (Panasonic WV-5300) was used to monitor subjects during testing, by observing facial, eye blinking, swallowing, tongue and mandibular jaw movements, and bodily movements. These bodily movements may introduce unwanted artifacts during testing.

A spectrum analyzer (Hewlett Parkard 3582A) permitted the detection spectrum of the stimuli. The enhanced color display (IBM model) was the main part of the display section. For example, the averaged, as well as the ongoing raw data are displayed on the screen as testing is in progress. In addition, waveform analyses can be made while testing. Furthermore, the most current waveform can be compared with waveforms previously obtained. Upon observing the waveform collected, the experimenter had the option of rejecting or saving the obtained information. The investigator could also decide whether to interrupt the program and make a re-run of data. The IBM Proprinter II, printer and plotter (IBM Color Plotter) was used to print and plot respectively, the waveforms of the data collected.

Signal Processing (SP_1) Program: The SP_1 program operates in a similar manner as the SA program. It is used to analyze data that have already been collected. In addition, it permitted the experimenter to plot data on the plotter. It also made it possible for the

investigator to normalize, filter, or scale the axes of the output waveforms.

Further, a sub-program (dcbat.bat) was installed under the SP_1 processing program. This program made it possible to tabulate values of latencies and amplitudes of single or multiple waveforms by normalizing their dc shifts. In this manner a uniform baseline was maintained for all waveforms analyzed.

Some Signal Enhancement Techniques Employed: In addition to the previously-mentioned signal enhancement techniques (e.g., use of shielded phones and medial earlobe electrode placement), the following methods were found to be useful in enhancing waves I' and I of the BAEP.

(a) Increasing the number of trials in stimulus presentation: The noise level during testing can be decreased by increasing the number of samples (Coats, 1983; Glasscock et al., 1987). In the present study the number of samples was increased from 1,024 for 3.22 stimuli per second to 4,096 samples for 96 stimuli per second repetition rate.

(b) Decreasing analysis time from ten to five milliseconds: By decreasing the analysis time from 10 to 5 ms, this permitted one to enhance the detection of the first three the first three waves of the BAEP. Furthermore, the method permitted a higher resolution by using an increased number of data points and a decreased dwell time.

(c) Intra-tympanic electrode placement: In order to record a more robust response, an intra-tympanic electrode placement was employed. Thus, waves I and II were enhanced. Previous studies have supported

the notion that as the distance between the recording electrode and the generator is increased, the amplitude of the BAEP is increased (Moller and Moller, 1985).

CHAPTER IV

SPECIFIC PROCEDURES AND RESULTS

In this chapter a presentation is made of the findings of waves I′, I, III, and V of the BAEP from 58 normal human subjects. Since wave I′ is the primary focus of this investigation, it was compared to waves I, III, and V using latency and amplitude as the dependent variables. The goal of the investigation was to determine if the behavior of wave I′ was similar to the remainder of the waves of the BAEP. If so, these data may reveal fundamental information as to whether wave I′ is of neural or cochlear origin. To achieve this goal, wave I′ was observed under five experimental conditions in which click and toneburst acoustic stimuli were presented at suprathreshold intensity levels. To be more specific, latency and amplitude of these potentials were analyzed in relation to wave I′, to variables such as intensity level, stimulus polarity, filter settings, forward-masking and repetition rate. The forward-masking paradigm was used in order to provide additional information about the behavior of wave I′ under the variable of time in between the offset of the masker and the onset of the click stimulus, i.e., delta-T.

EXPERIMENT I - Latency and Amplitude as a Function of Click Stimuli

Equipment: A display of the apparatus used in this experiment can be found in figure III-1. Basically, an electrical pulse of 0.240 ms duration was used to generate an acoustic click of approximately 3.0 ms at the diaphragm of the earphone. Alternating, rarefaction, and condensation polarity were included as independent variables.

Subjects: Thirty-five, normal-hearing, female subjects were tested in this experiment. Subject selection procedures were the same as described in chapter III.

Procedure: The general procedure of subject preparation and electrode placement described in chapter III was used in this experiment. All thirty-five subjects were tested using three intensity levels of 70, 60, and 50 dB nHL and three click polarities of alternating, rarefaction, and condensation. Each condition was repeated twice on each subject in order to insure replicability. Electrophysiologic activity following each of a total 2,048 clicks at a rate of 10.21/sec, was averaged. A sampling rate of 100 kHz was used, which resulted in a dwell time of 10 microseconds. In this way, a total of 1,000 data points were available within a 10 ms analysis time. Responses obtained were analyzed in a 3 X 3 analysis of variance (ANOVA) experimental design.

Results: Waves I', I, III, and V were obtained and analyzed by calculating latency and amplitude. Within these two dependent parameters, the effects of the intensity and polarity series were

examined. In view of the fact that latency and amplitude of the BAEP tend to vary both between and within subjects and from one event to another, three distinct subgroups in the distribution curve were observed. These subgroups were previously identified as reducers, nonaugmenters, and augmenters (Amedofu, 1985). Since there is more variability of amplitude than of latency, the investigator deduced amplitude of the augmenters (N = 8).

Figure IV-1 displays the various BAEP waves recorded from subjects MA104911 and MB1049R1, which are representative of those obtained from the 35 subjects. As shown in the figure, data were collected in response to alternating, rarefaction, and condensation clicks at the three intensity levels of 70, 60, and 50 dB nHL. Waves I′, I, and IV-V were identified in the tracings. It can be seen, however, that waves I, III and V are readily identified at various phases of the click and at each of the intensity levels. In contrast, while wave I′ is identified regardless of the phase of the stimuli, identifiability becomes much more difficult as the intensity is decreased to the 50 dB level. It should be noted, however, that when I′ is present, it is a distinct wave which precedes wave I (e.g., see condensation condition at 70 dB nHL); but at times, it tends to be fused on the rising phase of wave I in certain of the conditions (e.g., see alternating condition at 70 dB nHL).

Figure IV-2 describes latency of wave I′ as a function of intensity and polarity. While effects of intensity were observed, i.e., latency decreased as intensity increased, the effects of polarity were more pronounced at the 50 dB level when compared to the

Figure IV-1. Representative brain-stem auditory evoked potentials from two subjects (MA1049L1 and MB1049R1). Phase and intensity conditions are nested in a three by three experimental design.

Figure IV-1

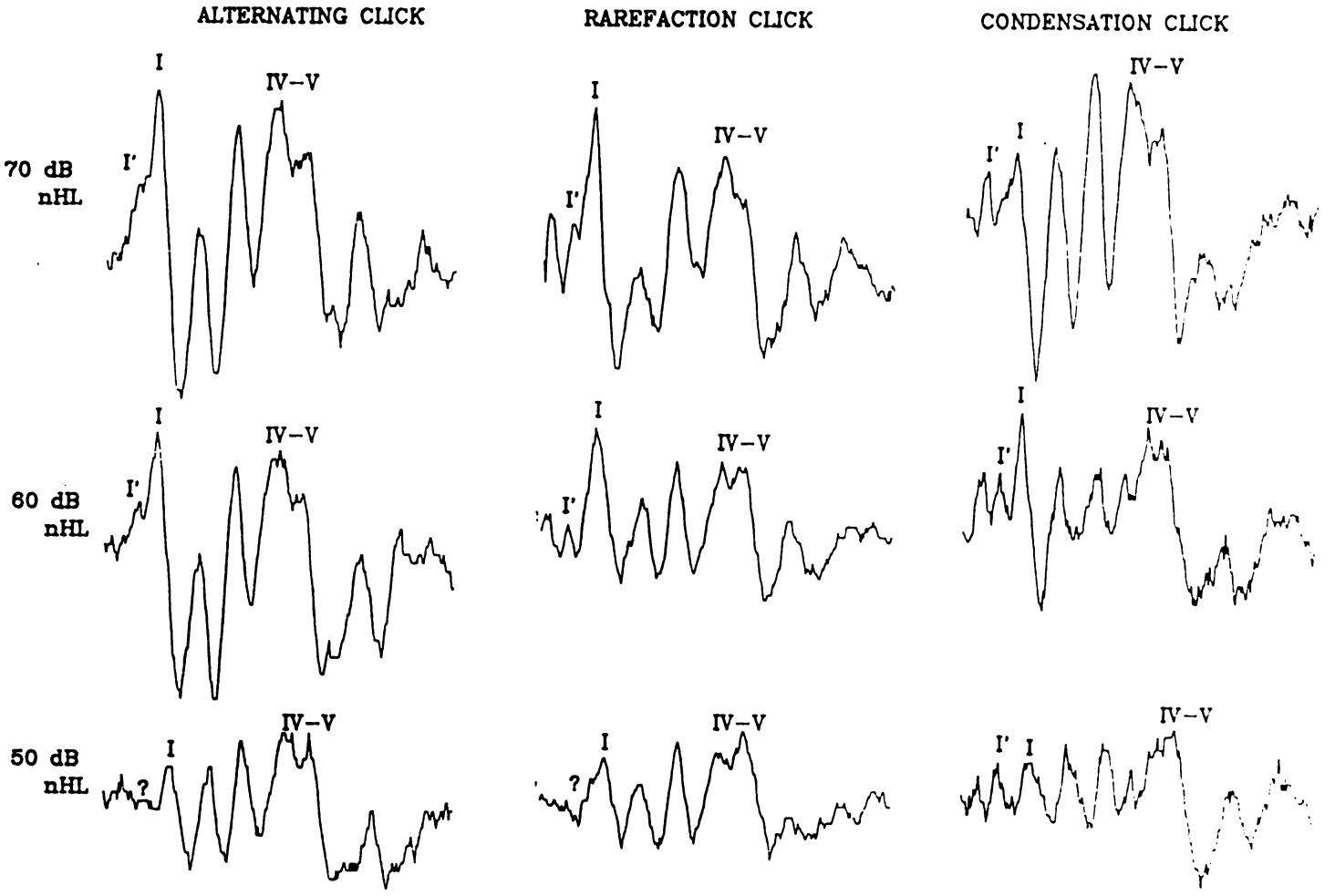

ALTERNATING CLICK
RAREFACTION CLICK
CONDENSATION CLICK
70 dB nHL
60 dB nHL
50 dB nHL
I
I'
IV–V
?

Figure IV-2. Summary of the wave I' latency as a function of intensity and phase. The higher the intensity the shorter the latency and the smaller the variation within each response.

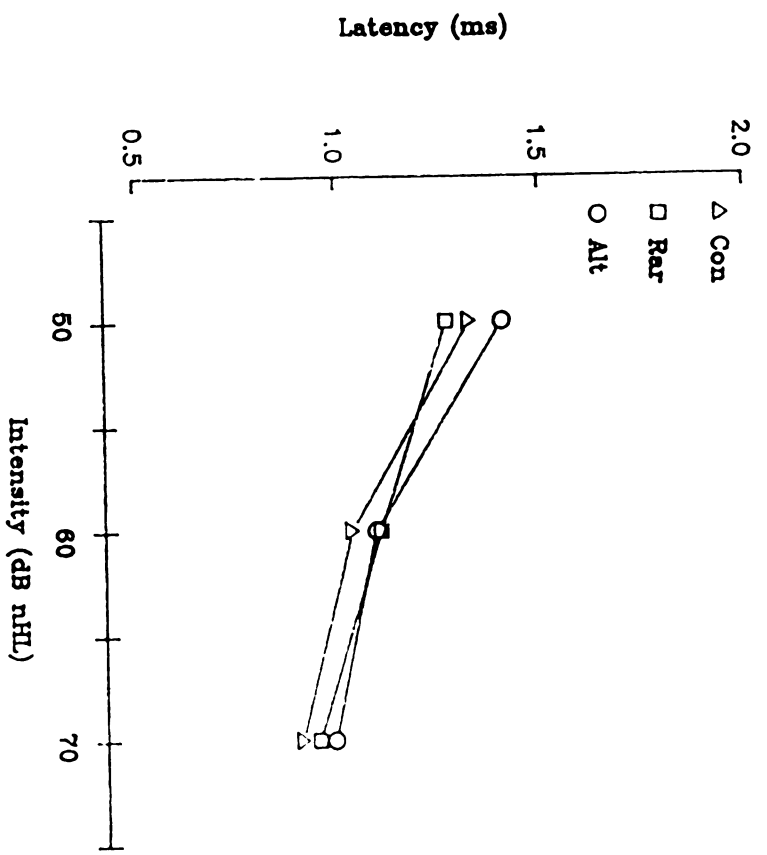


Figure IV-2

WAVE I'

Latency Series - Summary

the alternating data points are consistently greater in latency than either rarefaction or condensation.

Figure IV-3 compares Wave I' to the three waves of the BAEP, i.e, I, III, and V. This was done to compare wave I' with an evoked potential that is known to be generated by the distal (peripheral) part of the auditory nerve (wave I), the caudal part of the central auditory nervous system (wave III), and the more rostral part of the brain-stem (wave V). Figure IV-3 also displays the additional parameter of phase of the stimuli. Wave I' latency is consistent with the input-output functions obtained for the remainder of the waves. In other words, there exist parallelism for wave I' when compared to the functions of waves I, III, and V. Note that the latency of waves I' and I are closer together when compared to waves III, and V. Furthermore, wave I' latency appears to be more sensitive to phase at the lower intensity level.

Statistical data on the effects of intensity and polarity on latency of wave I', I, III and V appear in Appendix H. Wave I' latency has a statistically significant intensity main effect ($F = 36.12$, $P < 0.05$), but no significant polarity effects. Furthermore, no intensity-polarity interaction was observed. Waves I, III and V latency showed an identical statistical trend to that of wave I'.

Figure IV-3. Comparative view of the latencies of waves I', I, III, and V as a function of intensity and phase. Wave I' has a similar pattern as the rest of the brain stem auditory evoked potentials.

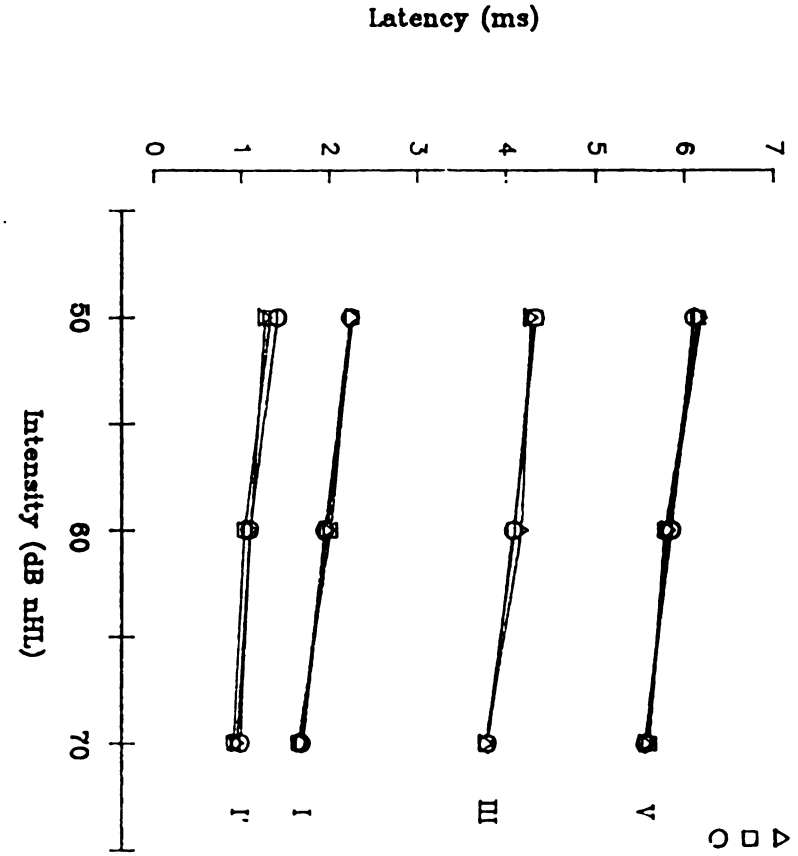

WAVE I' IN COMPARISON TO WAVES I, III AND V
Latency Series – Waves I', I, III and V
Latency (ms)
0
1
2
3
4
5
6
7
50
60
70
Intensity (dB nHL)
I'
I
III
V
Con
Rar
Alt

Figure II-3

Figure IV-4 shows wave I′ amplitude histograms as a function of intensity, with polarity as the parameter. Maximal amplitude of about 215 nV was obtained at 70 dB nHL for rarefaction and condensation clicks. The effect of alternating phase was less than that of rarefaction and condensation. However, both rarefaction and condensation amplitude showed higher variance than alternating clicks. Thus, alternating stimulus magnitude was less than for rarefaction and condensation responses at all levels, except 50 dB nHL.

Figure IV-5 permits a general comparative view of wave I′ with waves I and III. Amplitude output of wave I′ seems consistent with the magnitude of waves I and III at 70 dB nHL, but not as consistent at 60 and 50 dB nHL. It should be noted that higher magnitudes were obtained for condensation and rarefaction for waves I and III, which is consistent with the amplitude data of wave I′.

Statistical data representing effects of intensity on amplitude is shown in Appendix I. Wave I′ recordings showed that there was a significant intensity main effects ($F = 159.64$, $P < 0.05$); a statistically significant polarity main effects ($F = 14.40$, $P < 0.05$); and a statistically significant polarity/intensity interaction effect ($F = 6.17$, $P < 0.05$). An intensity level of 70 dB nHL produced higher amplitude magnitude than 60 dB nHL, which also had a significantly higher magnitude than 50 dB nHL. Significance of polarity/intensity interaction indicated that amplitude for 70 dB nHL intensity is more pronounced for rarefaction and condensation, than is for alternating polarity.

Figure IV-4. Wave I' amplitude histograms are shown as a function of intensity and phase. Rarefaction produced maximal amplitude of 215 nanovolts at 70 dB nHL.

Figure IV-4

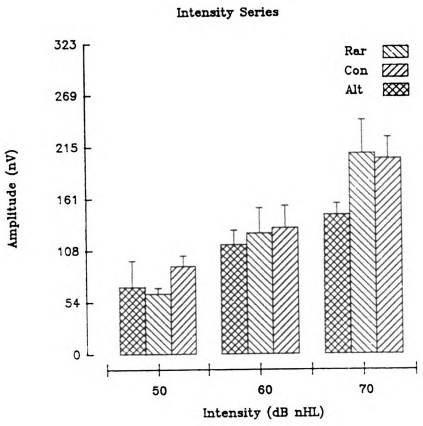
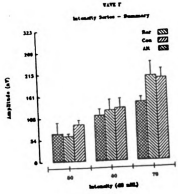
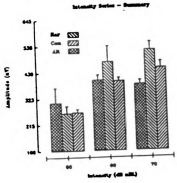
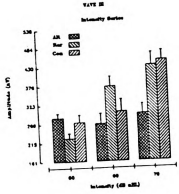

WAVE I'
Intensity Series
Rar
Con
Alt
323
269
215
161
108
54
0
Amplitude (nV)
50
60
70
Intensity (dB nHL)

Figure IV-5. Wave I' amplitude, as a function of intensity and phase, is compared with waves I and III via histographic representation.

Figure IV-5


WAVE V
Intensity Series - Summary
Ref
Con
AR
Intensity (dB nHL)


WAVE I
Intensity Series - Summary
Ref
Con
AR
Intensity (dB nHL)


WAVE III
Intensity Series
AR
Ref
Con
Intensity (dB nHL)

main effects ($F = 177.17$, $P < 0.05$), polarity main effect ($F = 53.36$, $P < 0.05$), and intensity/polarity interaction effect ($F = 29.63$, $P < 0.05$). In general, 70 dB nHL yielded a higher amplitude magnitude than 60 dB nHL, which also had a higher magnitude than 50 dB nHL. Both 70 and 60 dB nHL had the highest magnitude in rarefaction condition than either alternating or condensation polarities. On the other hand, 50 dB nHL had a slightly higher amplitude magnitude in alternating condition than either rarefaction or condensation. Wave V magnitude showed statistically significant intensity main effects ($F = 195.78$, $P < 0.05$), polarity main effects ($F = 8.60$, $P < 0.05$), and intensity/polarity interaction effect ($F = 6.54$, $P < 0.05$). The 70 dB intensity level resulted in a significantly higher amplitude than that of either 60 or 50 dB nHL. However, the amplitude output of the 60 dB nHL intensity levels was not significantly different from that of 50 dB nHL.

Summary of Experiment I Findings

Responses of the human auditory system to click acoustic stimuli that were presented at the rate of 10.21/sec were observed under six experimental conditions, nested in two factors, A (alternating, rarefaction, and condensation) and B (70, 60, and 50 dB nHL). It was investigated as to whether the six conditions had effects on two dependent variables, latency and amplitude. Further, it was examined if there were interactions between intensity levels and polarities. Wave I′, which is the focus of the investigation, was compared with

three waves of the BAEP, waves I, III, and V. While a statistically significant effects of intensity was observed for latency, similarly significant polarity effects on latency and intensity/polarity interaction were absent. In contrast, both intensity and polarity had significant effects on amplitude, with intensity and polarity interaction. Thus, wave I' results were very similar to those of waves I, III, and V.

EXPERIMENT II - Latency and Amplitude as a Function of Tonebursts

Equipment: The apparatus used in this experiment were the same as those described in the previous chapter. The nature of tone stimuli used was similar to the one shown in figure III-2D. A toneburst of 2 ms rise/fall time duration was used to generate and deliver a tone to the subject's ear. Rarefaction and condensation tonebursts were nested within tones of 500, 2,000 and 8,000 Hz.

Subjects: Five, normal-hearing, female subjects were selected for this experiment. The selection procedures were the same as those described in the previous chapter.

Procedure: Five subjects were tested with electrode placement as described in chapter III. The factors of toneburst (A) and intensity (B) were presented to each subject. Three experimental conditions were nested within each of the two factors. Factor A had three tonebursts of 500, 2,000, and 8,000 Hz, while factor B comprised 70, 60, and 50 dB nHL. To prevent the ambient noise as well machine artifact

during recordings, one millisecond time delay was introduced for low and high frequencies while middle tone had 0.5 millisecond delay time. Results: It can be seen in figure IV-6 that waves I, III, and V were present at the three frequencies and at the three intensity levels. While I' was present at 500, 2,000 and 8,000 Hz at 70 dB nHL, it was more difficult to observe the response at lower intensity levels, for both 500 and 8,000 Hz tones. Rarefaction at the 70 dB nHL level produced a clear wave I' response at all three tones. In contrast, condensation at the same level elicited identifiable wave I' only at 500 Hz.

Figure lV-6 also indicates that the low tone (500 Hz) at less than 70 dB nHL is poor at eliciting peripheral auditory waves (i.e. waves I', I, and II), while central auditory waves continue to be observed. Although wave I' was difficult to elicit at 60 dB when a 2,000 Hz tone was presented, wave I could still be seen.

Figure IV-7 displays latency sets as a function of frequency and intensity. Included also are the parameters of phase, i.e., rarefaction and condensation. In the top panel (500 Hz), it can be seen that condensation stimuli yielded shorter latencies than rarefaction stimuli. The middle panel shows results for the 2000 Hz stimuli, where latency is seen to decrease as a function of intensity.

At 8,000 Hz (lower panel), rarefaction yielded shorter latencies than condensation stimuli. In all cases, the normal variability is of a value which permits latency to be used as an index for confidence limits. Rarefaction shows shorter latencies at the higher frequencies and higher intensities. Thus, it can be seen that I' can be recorded

Figure IV-6. Analog responses elicited from subject SK0868R1. Responses are represented through a three by three experimental design. Phase is nested within each intensity level (50, 60, and 70 dB nHL) and each tone (500, 2,000, and 8,000 Hz).

Figure IV-6

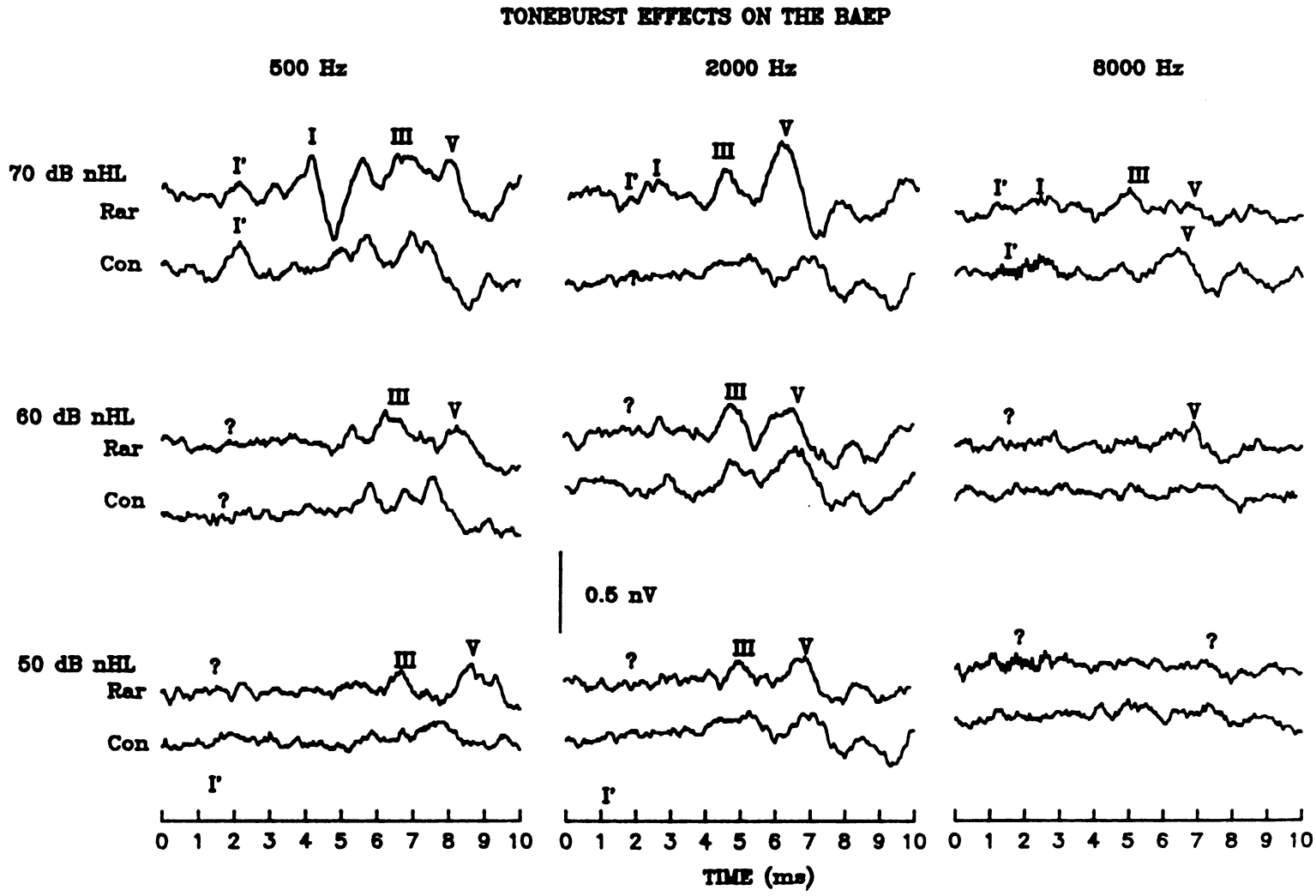
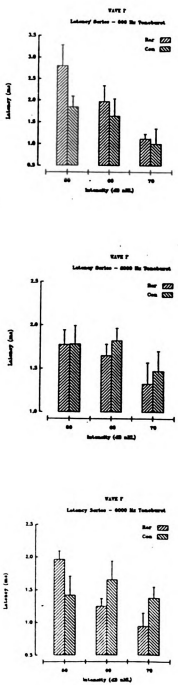

TONEBURST EFFECTS ON THE BAEP
500 Hz
2000 Hz
8000 Hz
70 dB nHL
60 dB nHL
50 dB nHL
Rar
Con
I'
I
III
V
?
0.5 nV
0 1 2 3 4 5 6 7 8 9 10
TIME (ms)

Figure IV-7. Wave I' responses is histographically represeted as a function on intensity (50, 60, and 70 dB nHL) phase (rarefaction and condensation) and tones (500, 2,000, and 8,000 Hz).

Figure IV-7


WAVE I
Latency Series - 500 Hz Tonebursts
Ear
Con
Latency (ms)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
60
70
Intensity (dB nHL)
WAVE I
Latency Series - 2000 Hz Tonebursts
Ear
Con
Latency (ms)
2.5
2.0
1.5
1.0
60
70
Intensity (dB nHL)
WAVE I
Latency Series - 4000 Hz Tonebursts
Ear
Con
Latency (ms)
2.5
2.0
1.5
1.0
0.5
60
70
Intensity (dB nHL)

at low, mid, and high frequencies, but is best seen at high intensity levels.

Figure IV-8 compares wave I′ as a function of frequency to that of wave I. Once again, the parameter is phase. The general trend of these data is that wave I′ latency tends to decrease as a function of frequency, very much like that of wave I, regardless of the phase. Thus, wave I′ appears to behave very similarly to that of the auditory nerve wave I. The lower frequencies tend to have greater variability than the higher frequencies and at the lower intensity levels.

In figure IV-9, comparisons of the amplitude data as a function of frequency can be seen in the far left panels (wave I′) or fat right panels (wave I), while comparison of wave I′ with wave I can be seen by reading across the upper (500 Hz), middle (2,000 Hz), or lower (8,000 Hz) panels. As the intensity is increased, amplitude increases, regardless of the phase of the stimuli or frequency of the stimuli. Rarefaction consistently has greater effects than condensation except for I′ at 8,000 Hz, 50 and 60 dB nHL (e.g., see figure IV-10). In general, there is greater variability for wave I′ than there is for wave I.

The three main effects of amplitude were frequency, intensity, and polarity. Wave I′ intensity ($F = 22.46$, $P < 0.05$) and polarity ($F = 10.28$, $P < 0.05$) were statistically significant, while frequency failed to reach statistical criterion. The interactions of these data revealed an intensity by polarity effect ($F = 3.37$, $P < 0.05$) and a frequency by polarity effect ($F = 5.28$, $P < 0.05$). Similar statistical effects were seen for waves I, III, and V (See appendix

Figure IV-8. Waves I' and I latencies are shown as a function of intensity (50, 60, and 70 dB nHL) and tones (500, 2,000, and 8,000 Hz).

Figure IV-8

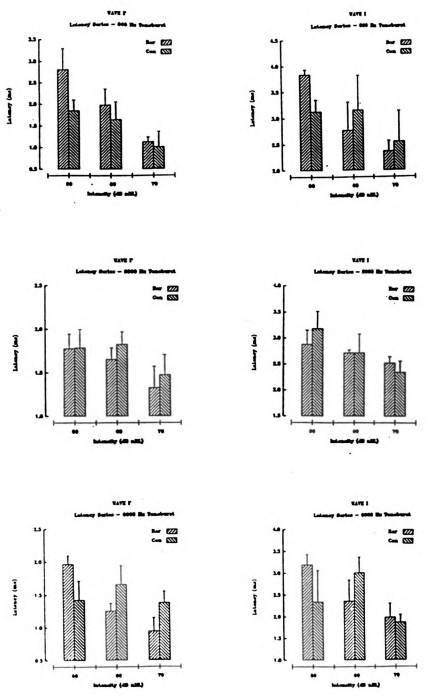


Figure IV-9. Histographic comparison of waves I′ and I amplitude as a function of intensity (50, 60, and 70 dB nHL) and tones (500, 2,000, and 8,000 Hz). Although wave I′ amplitude tended to have more variaton than wave I, patterns of one wave resemble those of the other.

Figure IV-9

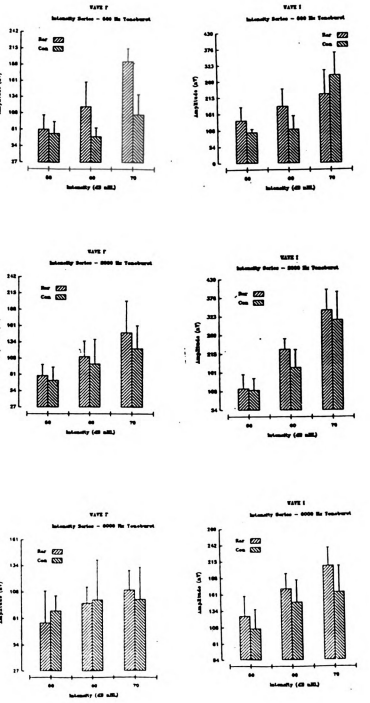
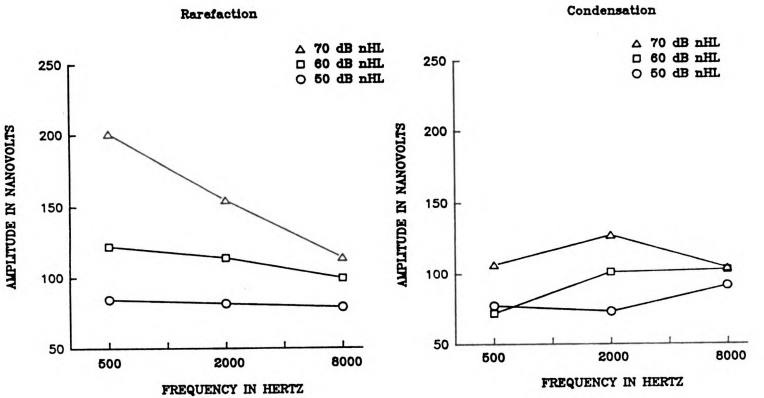


Figure IV-10. Graphical representation of amplitude by toneburst interactions. Tone and phase are independent variables.

Figure IV-10

WAVE I'
AMPLITUDE BY TONEBURST INTERACTION



J), and frequency showed a significant main effect.

Summary of Experiment II Findings

These data revealed that wave I' can be evoked by various frequencies, namely, 500, 2,000 and 8,000 Hz. For the most part, rarefaction stimuli yielded shorter latency and greater amplitude responses than condensation stimuli. While frequency was not statistically significant for wave I', it was significant for waves I, III, and V. There was a significant interaction for frequency and intensity for all waves, except wave I'.

EXPERIMENT III - The Effects of Filter Settings on the BAEP

Equipment: The equipment used was the same as described in the previous experiment. In order to focus more on wave I', an epoch of 5.0 ms was employed. Wave I', at times, cannot be recognized in the 10 ms epoch, but can be more readily identified in a 5.0 ms epoch. Stimuli were presented using alternating clicks at a rate of 10.21/sec. A special electrode, the Coat's leaf eartrode, was placed in the external auditory meatus.

Subjects: Eight, normal-hearing female subjects, with no history of hearing impairment, were tested in this experiment. Details on subject-selection criteria were the same as outlined in chapter III.

Procedure: Three electrodes were placed on the subject's head. Gold cup electrodes were placed at the vertex (Cz) and at the forehead

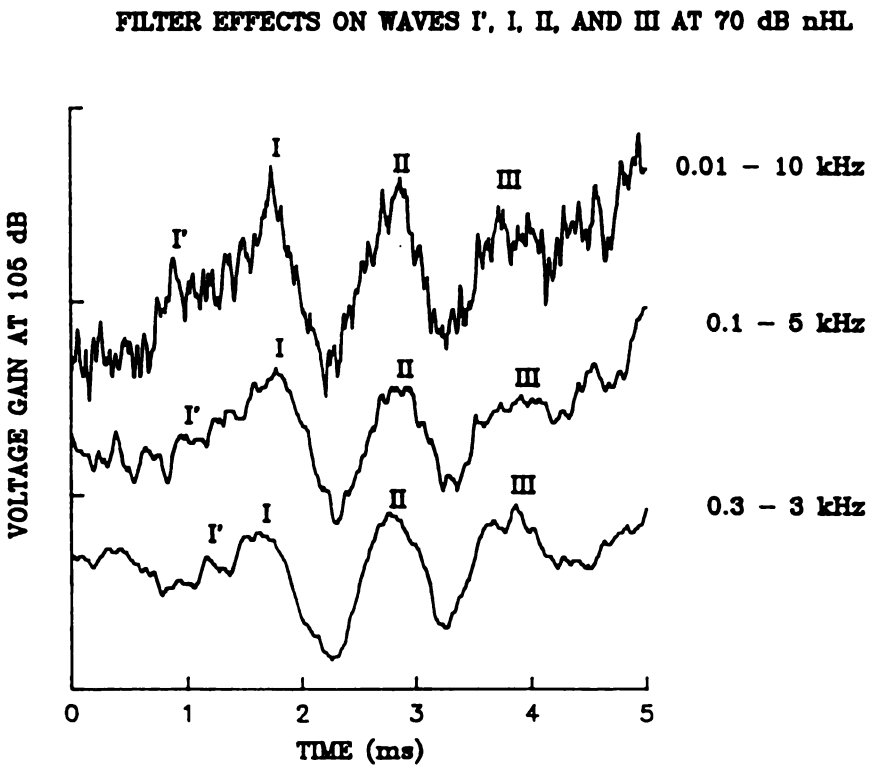
(FPz). Impedances were not allowed to exceed 2 kOhms. The eartrode was placed on a clean, inferior surface of the external auditory meatus, within the medial bony two-thirds. Impedance of the eartrode was kept in the region of approximately 25 kOhms. Recordings were made between the Cz and the eartrode in a differential manner. Since the objective of the experiment was to observe the filter-effects on wave I', seven of the eight subjects were tested at the constant intensity level of 70 dB nHL.

The bandpass filters through which responses were transmitted were controlled in the following manner: upper limits were fixed at 10,000, 5,000 or 3,000 Hz, while the lower limits were progressively increased from 10 Hz, to 100 Hz and 300 Hz. A series of forty traces was obtained from four subjects which provided a clear morphological view of responses from the cochlear through the cochlear nucleus. Results: Figure IV-11 presents responses obtained from one subject (SA0450R1) using the various bandpass conditions. In general, waves I', I, II, and III behaved in a similar manner in response to the various filter settings. However, the higher the low pass filter setting (e.g., 10 KHz), the higher the frequency noise was introduced into the traces. Thus, response identification is less certain, especially for wave I'. For low pass filter settings of 5 or 3 KHz, response identification is less confusing, especially for 3 KHz, since at this setting there are fewer oscillations prior to wave I'. Thus, wave I' is more readily identifiable using a more restricted bandpass setting for both the high and low bandpass settings.

These data, with regard to latency, can best be viewed in figure

Figure IV-11. Analog brain stem auditory evoked potential representation obtain from subject SA0450R1. The analog responses show that as the width of the bandpass filter decreases amplitude size decreases as well, while latency increases. Waveforms increasingly become smoother.

Figure IV-11


FILTER EFFECTS ON WAVES I', I, II, AND III AT 70 dB nHL
VOLTAGE GAIN AT 105 dB
I'
I
II
III
0.01 – 10 kHz
0.1 – 5 kHz
0.3 – 3 kHz
0
1
2
3
4
5
TIME (ms)

IV-12. This figure displays the latency of respective waves as a function of filter settings. It can be seen that once wave I' is identified, the latency of the response does not vary as a function of the low or high pass filter setting. Waves I and III show slight differences, but are not statistically different.

The tracings that were obtained seem to suggest the following points: (a) the wider the bandpass, the more detailed the tracings were obtained. The trade-off for the detailed information obtained was that the tracings elicited permitted contamination of high frequency waves and more equalization of the responses around the zero baseline; (b) wave I' could be recognized at suprathreshold levels, but as little as a 10 dB reduction of intensity was shown to obscure wave I', particularly for the 300-3,000 Hz range; (c) bandpass filter settings of 100-5,000 Hz seemed the most ideal condition for illustrating wave I', as well as waves following wave I'. For example, SP, double-peaked wave I', wave I knee, or double-peaked wave I were seen in some subjects when this filter setting were used; (d) bandpass filters that are commonly used in clinical situations are 100-3,000 Hz, and 300-3,000 Hz and were the filters used in this experiment.

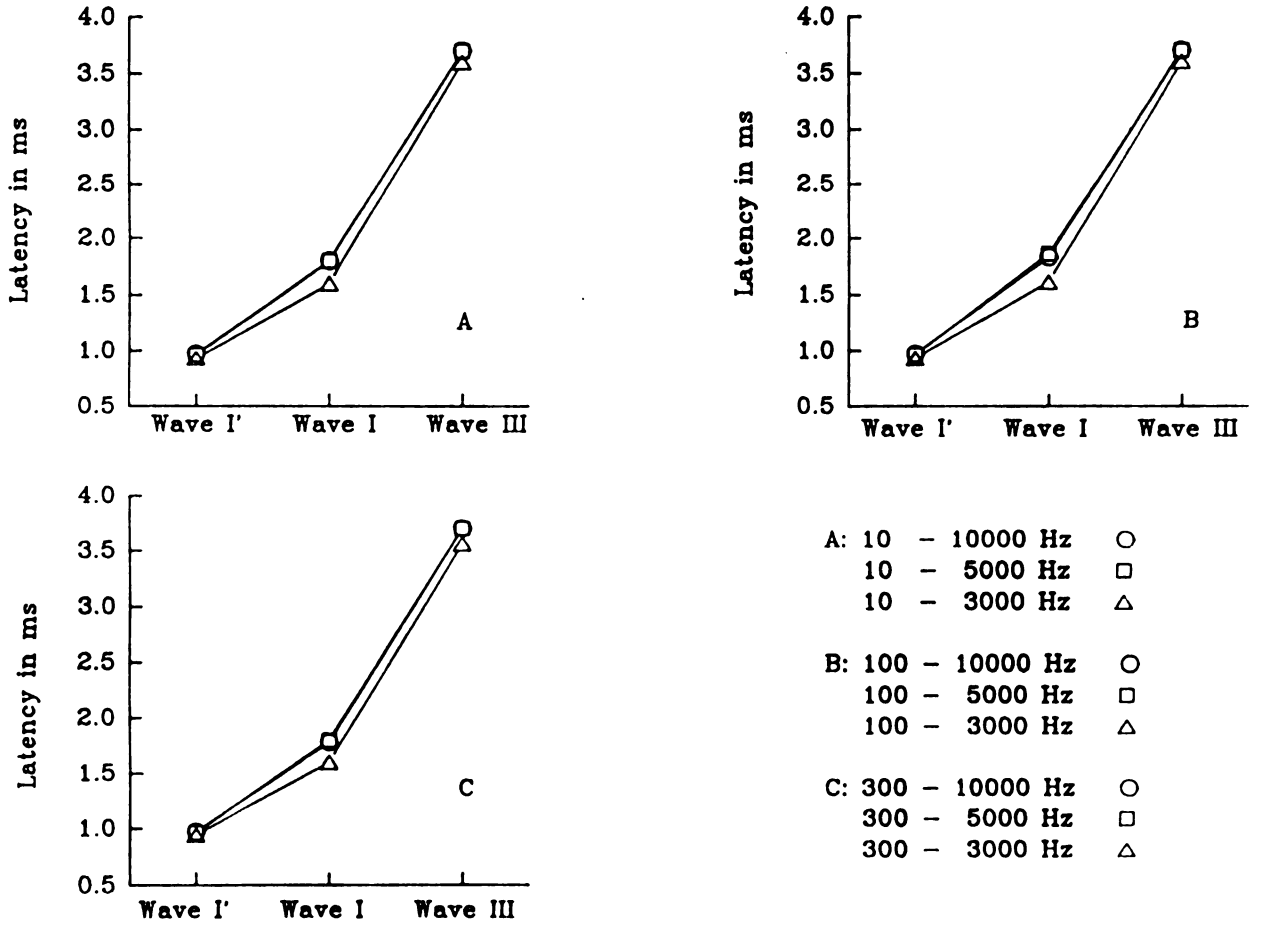
Summary of Experiment III Findings

In experiment III a qualitative evaluation of the effects of filtering was made. In an attempt to focus on wave I' of BAEP, the following variables were included in experimental conditions: the

Figure IV-12. Filter effects of narrowing a bandpass on waves I', I, and III. Narrower bandpass (10-3,000, 100-3,000, and 300-3,000 Hz) consistently produced shorter latencies for these waves.

Figure IV-12

FILTER EFFECTS ON WAVES I', I, AND III – LATENCY AT 70 dB nHL



"reference electrode" was placed closer to the generator in the ear canal than in the conventional far-field testing conditions. In addition, a 5 ms analysis time and progressively narrowing bandpass filter settings (i.e., from 10-10,000 Hz to 300-3,000 Hz) were employed.

EXPERIMENT IV - Effects of Forward Masking on the BAEP

Equipment: Equipment used for the experiment appears in figure III-1, with an additional white noise channel.

Subjects: Data were collected from five, normal-hearing female subjects. Subject-selection procedure and rationale for selection were the same as described in chapter III.

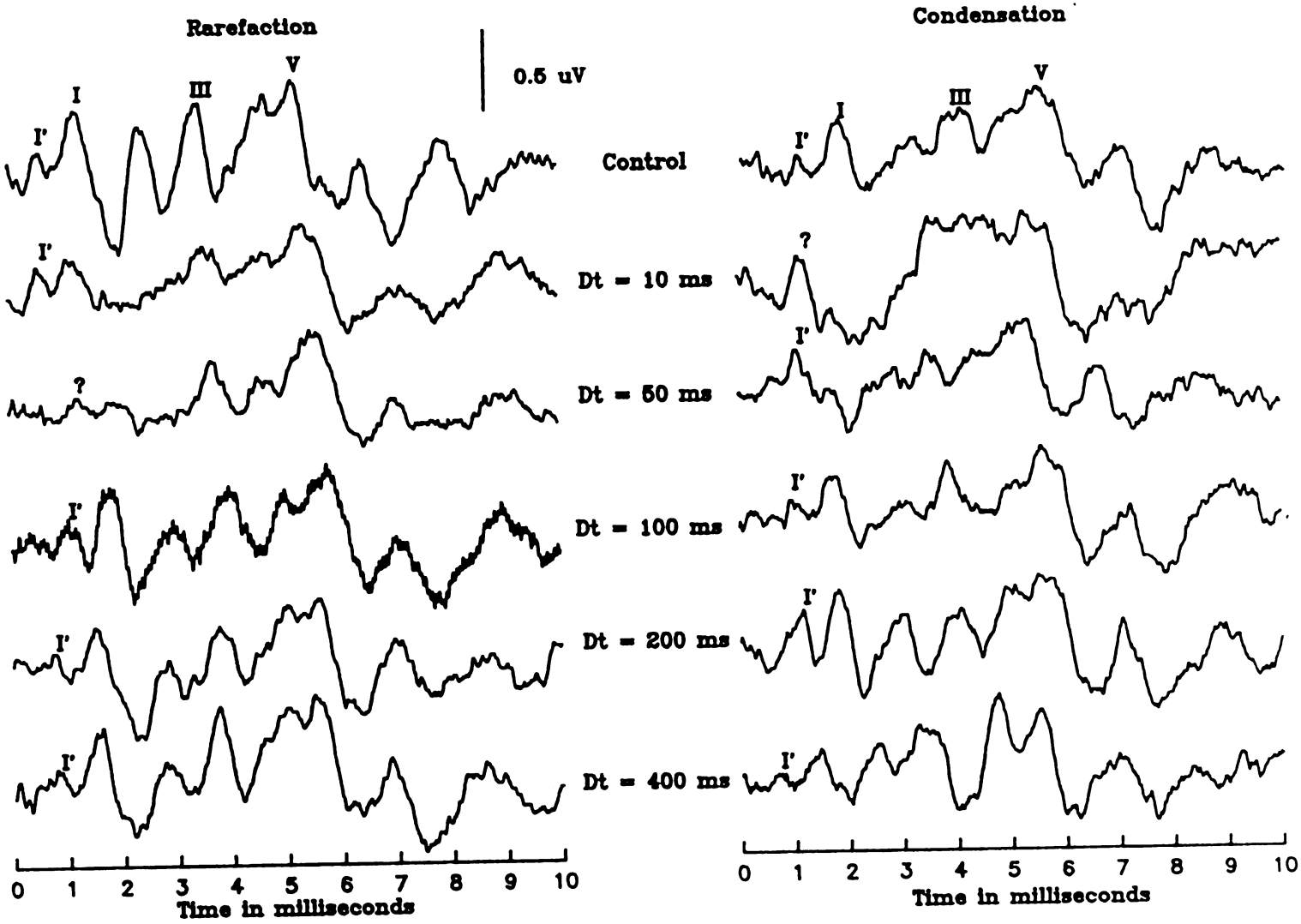
Procedure: The forward-masking paradigm used in the experiment is illustrated in figure III-2E. The procedure entails presentation of noise, the masker, followed by a click. The independent variable in the experiment is the time that elapses before noise and the click, called delta-t. In the present experiment five delta-t variables were considered, 10, 50, 100, 200, and 400 ms.

Results: We see in Figure IV-13 analog traces obtained from a typical subject in relation to various times between the offset of the noise and the onset of the click (delta-t). The control trace reveals waves I′, I, III, and V. Wave I′ can be readily seen as it precedes the appearance of wave I. As delta-t is increased (an increase in interstimulus interval), the latency of all waves tends to increase out to the time of 100 ms. As delta-t is increased beyond 100 ms, the

Figure IV-13. Latency as a function of delta-T (Dt) and phase in a forward-masking paradigm. Six experimental conditions were included under delta-T (control, 10, 50, 100, 200, and 400 ms). Phase included rarefaction and condensation.

Figure IV-13

LATENCY AS A FUNCTION OF DELTA-T IN A FORWARD MASKING PARADIGM



waves are observed to recover in their latency, i.e., latency becomes progressively shorter. Figure IV-14 provides the difference, if any, between delta-t and phase of the click stimuli. It can be seen that there are some minimal differences—in that latencies are shorter for rarefaction stimuli, especially at a delta-t equal to or greater than 100 ms.

Figure IV-15 displays the amplitude of wave I′ as a function of delta-t and phase of the click. The rarefaction stimuli consistently produced responses of greater magnitude than condensation stimuli. Once again, the effects of a more restricted delta-t can be seen as pertains to amplitude. It is to be noted that the variability is quite large, attesting to the fact that amplitude is quite variable, unless one uses all augmenters.

In general, statistics pertaining to this experiment showed no significant differences for both dependent variables (i.e., latency and amplitude) of the BAEP. These statistical values appear in appendices L and M. From these calculations it is evident that the P values for all waves are significantly large.

Summary of Experiment IV Findings

While statistical assessment of wave I′ shows a similar pattern to that of the waves that follow, in terms of latency and amplitude magnitude, analog data reveal a significant relevant pattern in all BAEP waves. The responses showed that as delta-t increased from 10 to 100 ms, latencies of all waves also increased. However, as the

Figure IV-14. Histographic representation of latency as a function of delta-T (in milliseconds) for wave I′ in a forward-masking paradigm.

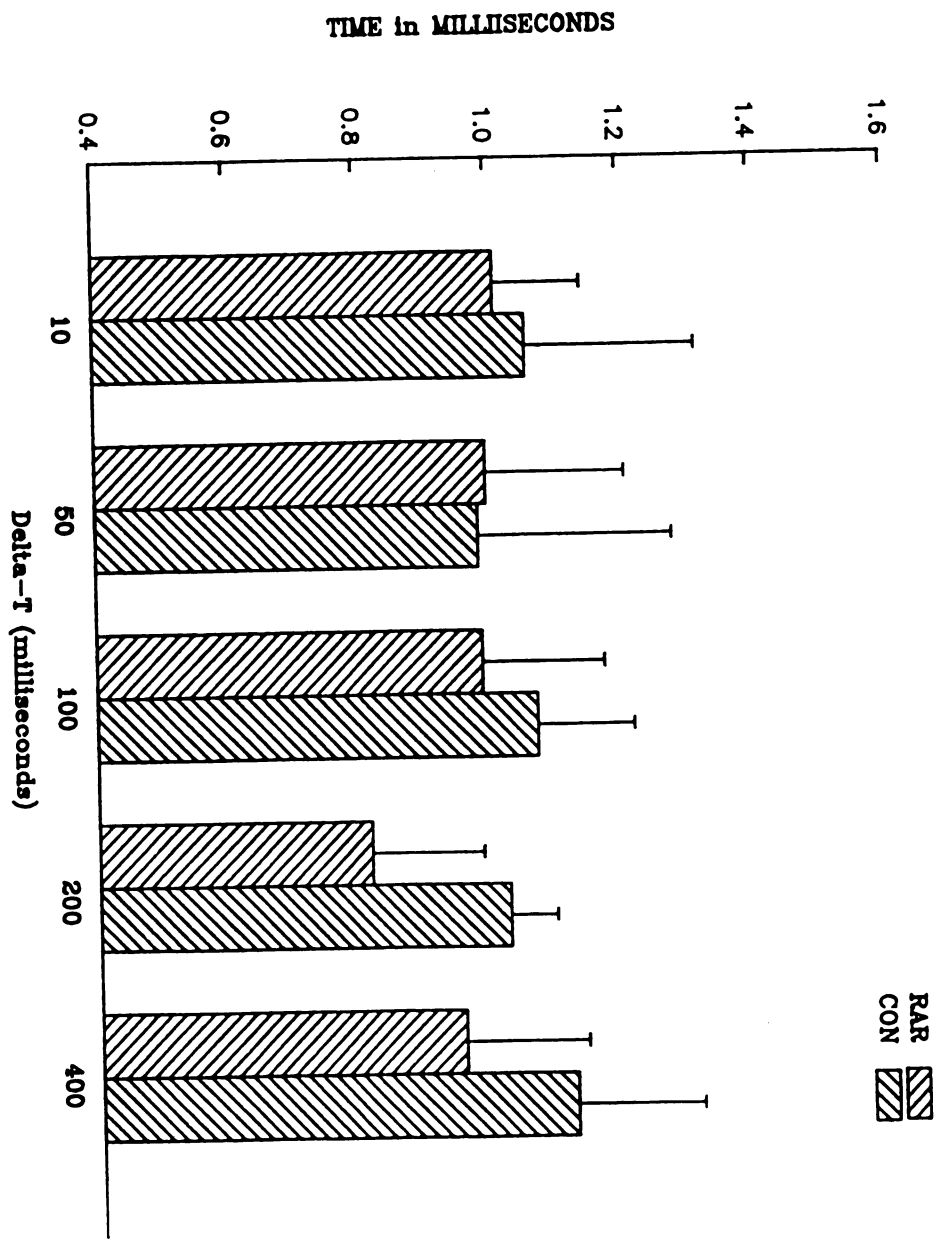


Figure IV-14

WAVE I' as a FUNCTION of Delta-T

Figure IV-15. Histograpic representation of wave I' amplitude (in nanovolts) as a function of delta-T (in milliseconds) in a forward-masking paradigm.

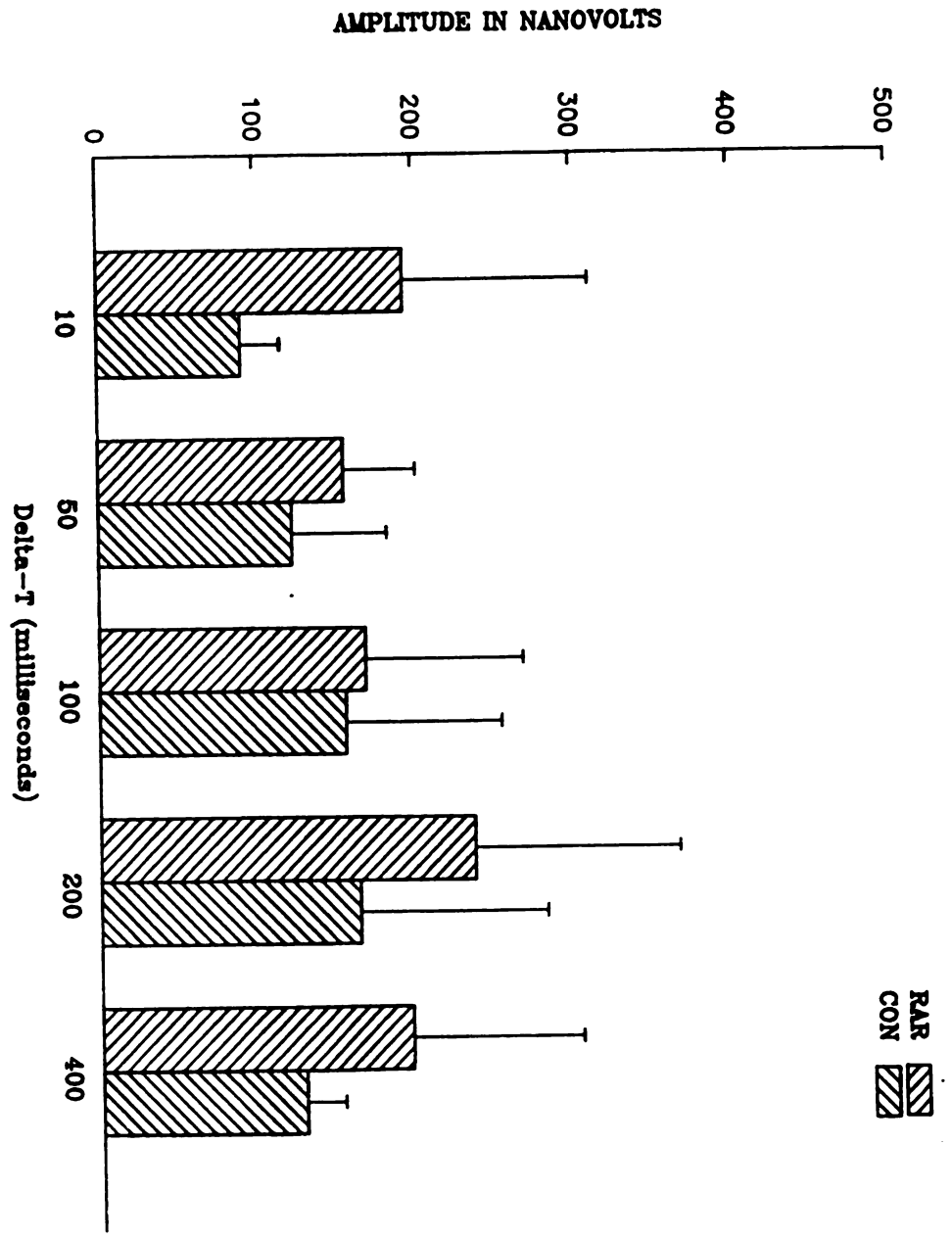


Figure 19-15

WAVE I' as a FUNCTION of Delta-T

interstimulus exceeds 100 ms, the potentials are inclined to recover but not fully. In addition, it was found that amplitude responses had greater magnitude for rarefaction than for condensation.

EXPERIMENT V - Effects of Repetition Rate on the BAEP

Equipment: Equipment for this experiment was set in the same way as shown in figure III-1. Click stimuli were presented as shown in figure III-2A.

Subjects: Five, normal-hearing female subjects were selected for this experiment. The selection procedures were the same as those described in chapter III.

Procedure: Subjects were prepared in accordance with procedures described in previous sections. Subjects were presented with pulses in the manner illustrated in figures III-2A and B, at the rates of 3.22, 10.21 and 96.00 stimuli per second. These stimulus rates were considered suitable for eliciting representative neural behavior of the auditory pathway as they covered a wide range of rates.

Results: We see the effects of repetition rate and phase on the waves in figure IV-16. All waves could be identified at the slow repetition rate of 3.22 and 10.21/sec. However, when a rate of 96/sec was employed, all waves were reduced in amplitude and prolonged in latency. The effect is more pronounced for waves III and II, less so for I and I'. The morphology of the waveform is altered as the repetition rate is increased. Figure IV-17 displays latency, while

Figure IV-16. Repetition rate as a function of latency and phase at 70 dB nHL. As repetition rate increases: amplitude is reduced, latency increased, and waveform morphology is distorted.

Figure IV-16

REPETITION RATE AS A FUNCTION OF LATENCY AND AMPLITUDE AT 70 dB nHL

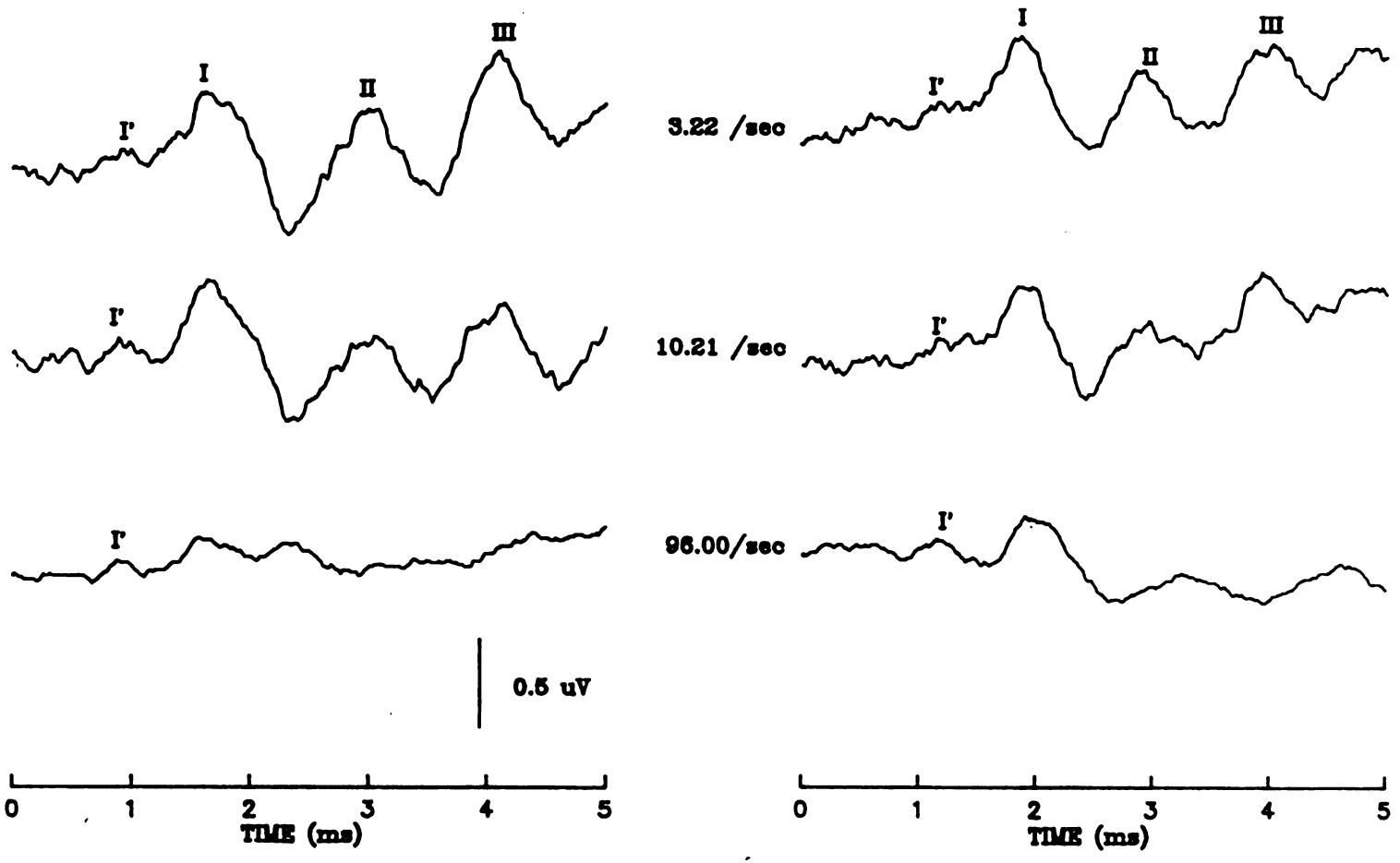


Figure IV-17. Comparative view of latency as a function of repetition rate and phase for waves I', I, and III. While a parallel pattern is observed for wave I when the three rates (3.22, 10.21, and 96 stimuli per second) waves I' and III show strongest agreement for 10.21 stimuli per second.

Figure IV-17

LATENCTY AS A FUNCTION OF REPETITION RATE

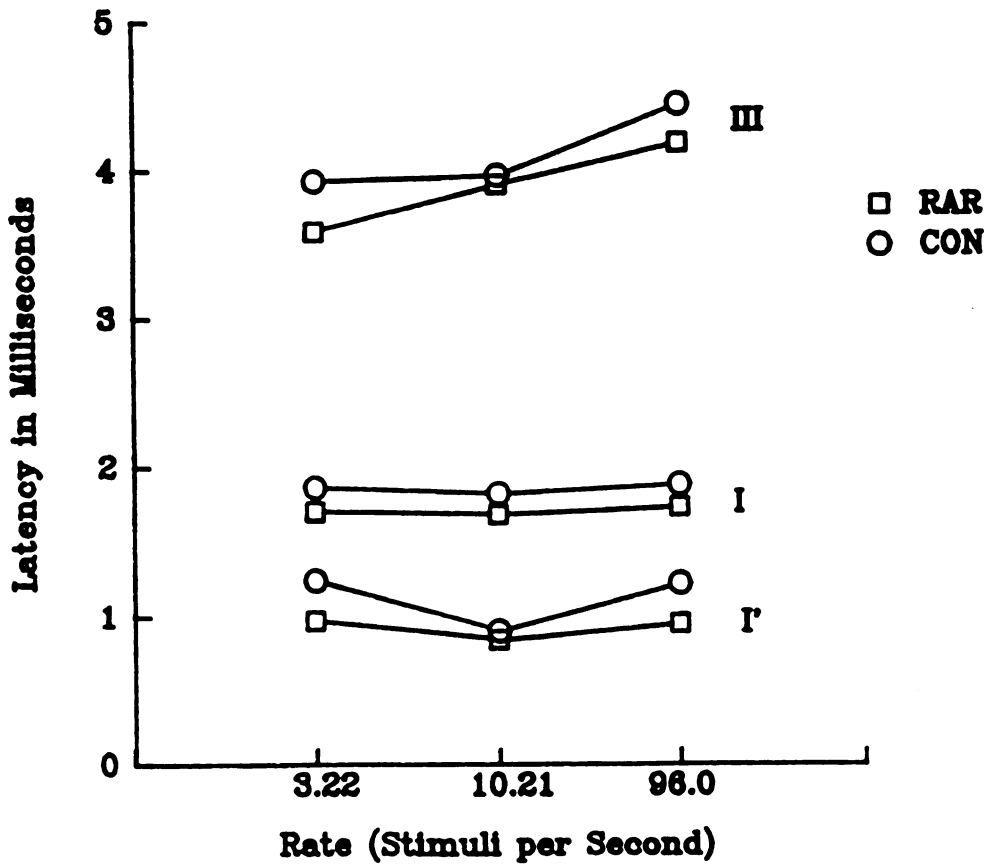


figure IV-18 displays amplitude.

Figure IV-17 shows that wave I′ rarefaction latency responses are consistently shorter than those of condensation, except at the 10.21 stimuli per second, where both phases produce equal latencies. Rarefaction results in shorter latencies than condensation in waves I and III as well. While wave I responses show an almost parallel input-output graph, rarefaction is superior to condensation for this potential. Waves I′ and III show an identical pattern in that condensation produces longer latencies at low and high repetition rates and tallies with rarefaction only at the mid-rate (10.21/sec).

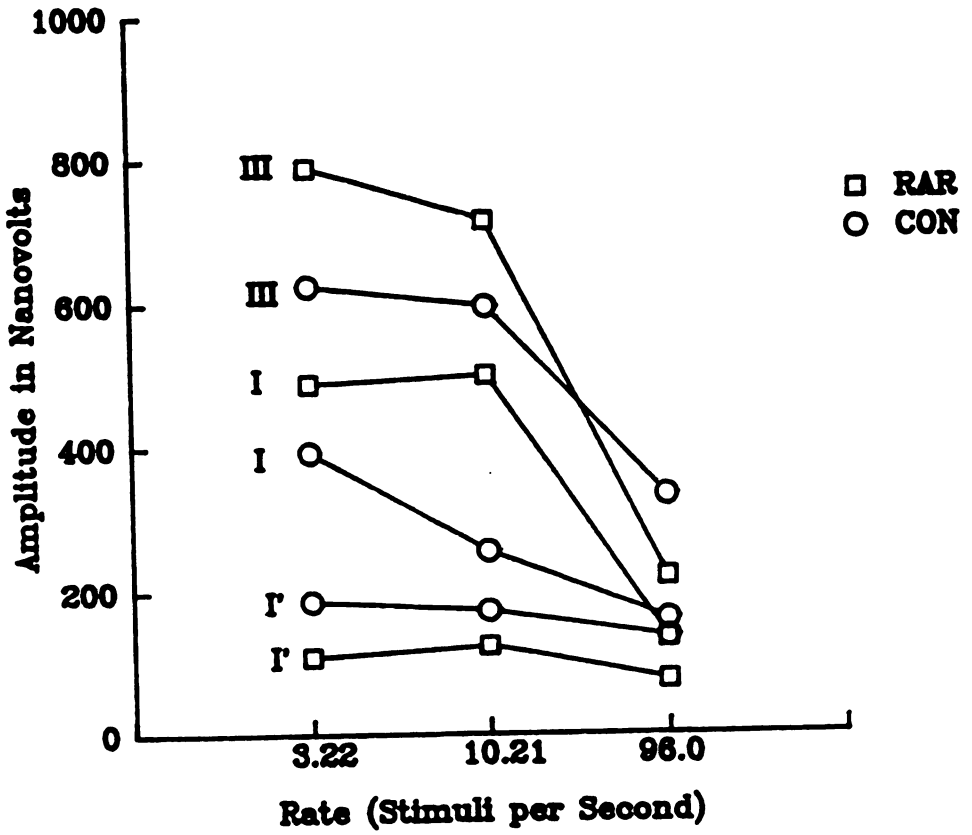
Amplitude magnitude of waves I′, I, and III are shown in figure IV-18. In general, condensation produced larger amplitudes for all low, mid, and high repetition rates than rarefaction. Waves I and III show this pattern only at 96.0 stimuli per second. In comparison with the remaining waves, the opposite is true for low and mid repetition rates. It should be noted that only at the low and mid rates does the amplitude magnitude appear in a clear and distinct manner. All waves display a noticeable drop of amplitude at 96.0 stimuli per second.

Wave I′ latency responses revealed statistically significant main effects independent variables, repetition rate ($F = 10.67$, $P < 0.05$), and polarity ($F = 18.26$, $P < 0.05$). Interaction between these variables was found to be insignificant. The pattern of statistical significance for wave I′ is identical to that of waves I and III.

Figure IV-18. A comparative view of amplitude as a function of repetition rate and phase. A marked decrease in amplitude is seen at 96 stimuli per second.

Figure IV-18

AMPLITUDE AS A FUNCTION OF REPETITION RATE



Similar to latency output, the magnitude of wave I' amplitude showed statistically significant values for repetition rates ($F = 3.48$, $P < 0.047$) and insignificant interaction between these variables. For wave I, the repetition rate appeared as the only factor ($F = 49.06$, $P < 0.05$). No statistically significant effects were found for either polarity or interaction between polarity and repetition rate. In contrast, wave III amplitude revealed statistically significant effects for the main effects as well as the interaction between them. Their F values were 81.94, 28.23 and 15.90 for repetition rate, polarity and repetition rate/polarity interaction respectively. In all cases the P value was 0.05.

Summary of Experiment V Findings

The analog data show that as repetition rates increase, morphology of the BAEP is progressively distorted. The data also shows that rarefaction responses are more affected at 96.0 stimuli/sec. than condensation. Waves I' and III rarefaction resulted in a more stable pattern of latencies than condensation. A definite parallelism is displayed by wave I at all repetition rates. The low and mid repetition rates show a distinct amplitude pattern in their dispersion. In contrast 96.0 stimuli/sec. resulted in a reduced cluster of magnitudes.

CHAPTER V

DISCUSSION OF RESULTS AND CONCLUSIONS

The main emphasis of this investigation was directed toward determining whether human wave I′ of the BAEP was neural or non-neural in origin. To achieve the objective of this goal, five experiments were performed on a 58, normal-hearing, female subjects. Within each experiment, several parameters were nested, including independent variables such as intensity levels, phase, tone, filter settings, and repetition rate. Dependent variables in these experiments were latency and amplitude. Wave I′ was analyzed through these parameters and compared with the known neural response within and outside the central nervous system.

Several general patterns became evident from the click data found in Experiment I. First, wave I′ is a small, intensity-dependent response that is clearly observed in most normally-hearing individuals at the highest suprathreshold levels. Second, alternating and rarefaction were better perceived by the ear at the highest intensity levels than a condensation click. Third, alternating phase resulted in the longest latency output at 50 dB nHL while rarefaction had the shortest latency. Although at 70 dB nHL wave I′ click stimuli produced very tight latencies, around 1 ms, alternating phase still revealed the longest latency value. A pattern similar to the BAEP, wave I′ output amplitudes increased as input intensity level increased. However, alternating phase stimuli produced amplitude of

reduced magnitude in a gradual manner. At 70 dB nHL, rarefaction clicks resulted in the in highest output of about 215 nV. In general, phase showed no significant differences at different levels of presentation, while intensity effects were consistently distinct.

Figures IV-3 and VI-5 show a latency and amplitude comparison of waves I′ with waves I and III. From the second figure it is apparent that the only difference between wave I′ and the remaining two waves is in size of amplitude output. These responses reveal an identical pattern which supports the interpretation that wave I′ is possibly a neural response that happens to be small and often overlooked or incorrectly identified as an epi-phenomenon, cochlear microphonic, or summating potential. It is apparent, therefore that wave I′ is a neural response that is readily masked when stimulus is presented at low intensity. It becomes clear at the highest and most comfortable intensity level.

The focus of the second experiment was to determined if wave I′ was tone-specific and whether this potential was as intensity-dependent as it proved to be for click stimuli. Besides addition of tone stimuli and elimination of the alternating phase, the rest of the parameters used in this experiment are the same as parameters considered in the previous experiment. To examine a tone and intensity effect on latency and amplitude output, the results were analyzed in a 2 x 3 factorial design, whereby factor A was polarity (rarefaction and condensation) and while factor B was intensity. Low (500 Hz), mid (2,000 Hz) and high (8,000 Hz) were nested within factor A.

In general, wave I′ latencies were similar to those elicited with click stimuli, in view of the fact that latencies grew shorter

as stimulus intensity level increased. For the 70 dB level, results obtained were similar to those previously obtained in Experiment I. The similarity occurred at 500 Hz through rarefaction and condensation, and at 8,000 Hz through rarefaction. Responses to middle tones at 70 dB level were generally longer than those elicited by clicks. In addition, a large variation of responses occurred. Furthermore, increase of stimulus intensity, from 50 to 60 dB nHL seemed to have no effects when mid-tones were presented through condensation phase. Responses of wave I′ latencies appeared similar to those of wave I as seen figure IV-9.

Wave I′ amplitude responses presented distinct patterns at all levels of tone and intensity. The highest responses evoked with 70 dB nHL tone stimulus were found to be about 215 nV. The second and third highest responses were observed at middle and high tones, respectively. In general, rarefaction phase produced higher amplitude output at all intensity and tone levels.

The fact that wave I′ amplitude responses trends appeared the same as wave I amplitude seems to verify the interpretation that wave I′ is a neural response. It is also apparent that wave I′ can be evoked not only by high tones but low as well. Considering the fact that wave I′ appeared distinct at 70 dB nHL, when tones of 500 and 2,000 Hz were presented through rarefaction, seems to be consistent with the findigs of Kiang (1965) who pointed out that the BAEP is a high frequency phenomenon in which not all neural fibers respond. In addition, Schwartz and Berry (1985) recommended the use of rarefaction in clinical auditory brain-stem response testing for best responses. Considering the fact that wave I′ responses found in this

experiment fit those findings, it seems to suggest that the potential is of neural origin.

In Experiment III, wave I′ was observed when bandpass filters were varied from a wide to a narrow filter passage in a systematic manner. The emphasis of the experiment was directed at qualitatively observing the morphology of the analog responses. In addition, individual subject responses were considered. For additional data on bandpass effects, wave I′ was compared with waves I and III in terms of their latencies.

From figure 12 panels A, B, and C, it is clear that wave I′ is in synchrony with the remaining waves of the BAEP. This experiment supports the view that wave I′ a neural response. In addition, the analog data displayed in the forward-masking paradigm (figure IV-13) and the repetition rate (figures IV-16, 17, and 18) show the behavior of wave I′ to be the same as the rest of the short latency responses.

From the present investigation, a conclusion is drawn to the effect that wave I′ is of neural potential. It is necessary to carry out more investigation on the notion of EPSP-like in animal studies, since TTX may not be used on animal subjects. It is also necessary to investigate the conditions under which wave I′ rides on the ascending phase of wave I as this will distinguish SP from wave I′. The present investigation indicates that in some subjects the use of certain filters can totally obliterate wave I′. It is recommended that more filter studies are performed between and within subjects so that an insight can be gained.

In view of the fact that there is an increasing number of teen-age mothers, homelessness, and slum conditions in inner cities, the

birth rate of neonates on the high risk register is likely to increase. This condition is worsened by the fact that many mothers are exposed to chemical agents which may poison the child in the fetal stage, thus placing the child on the high risk register. The wave I′ test may serve a significant screening device of children on the high risk register. The fact that it is a suprathreshold test gives it an advantage of being applicable in the intensive care units, where there may be noise from the incubators and various kinds of monitoring devices. Thus, detection of wave I′ in infants has the promise of being an effective diagnostic tool.

As a rehabilitative device, the wave I′ test may offer insights into the neural condition of the inner ear in cochlear implant candidates. This is so because the test makes cochlear neural function possible.

Conclusion

Wave I′ as a neural potential of the BAEP holds promise for future research and clinical applications. The previously-named potential studies may explain the functions of the cochlear—hearing loss due to ototoxic drug ingestion, noise-induced hearing loss, and presbycusis.

Recommendations

In view of the fact that the present investigation used only young to middle-age, normal-hearing, female subjects in order to rule

out variability that may result from gender and age differences, it is recommended that studies be made in the following population groups:

(1) Wave I' as a function of gender and the degree of differences if any;

(2) Wave I' as a function of age and possible longitudinal study that will indicate if latency of this wave shorten in a similar way as wave V in early childhood;

(3) An investigation into the behavior of wave I' for different types of hearing losses and severity;

(4) A comparative study of wave I' cochlear implant patients and hearing aid users with sensori-neural hearing loss diagnosis; and

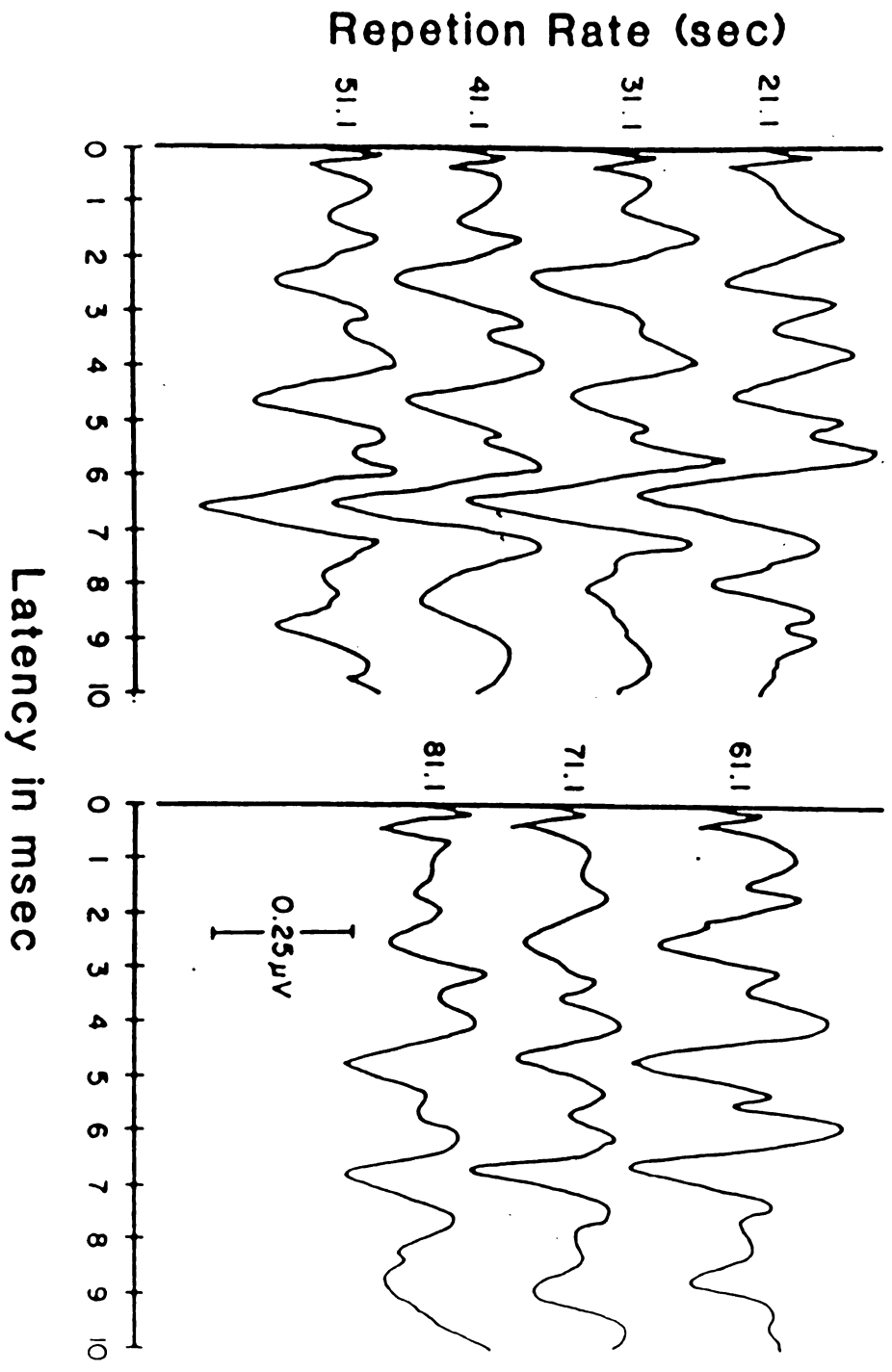
(5) Analysis of the wave I' of the BAEP in drug-dependent pregnant mothers and their offsprings.

APPENDICES

APPENDIX A

Changes in ABR Characteristics Secondary to Increasing Repetition Rate.

APPENDIX A



Changes in ABR characteristics secondary to increasing repetition rate.

APPENDIX B

Illustration of Increasing Repetition Rate for ABR with Normal Subject.

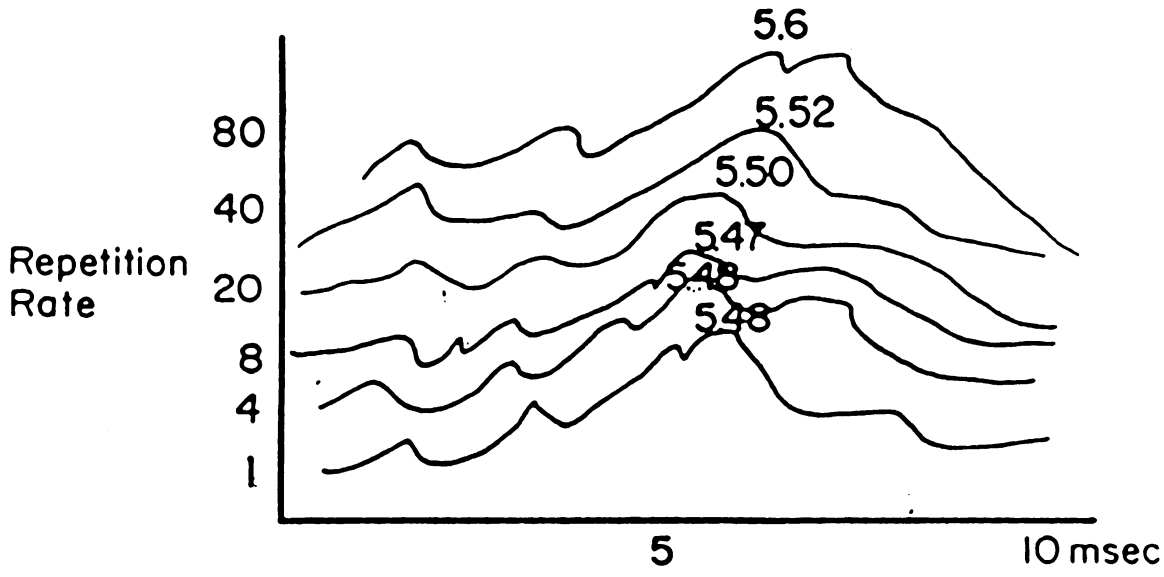


Illustration of increasing repetition rate for ABR with normal subject. Note both latency shift and loss of detail at high rates. N = 1024, I = 85 peSPL with 0.1 msec click.

APPENDIX C

Adult Case History Hearing

APPENDIX C

ADULT CASE HISTORY
HEARING

NAME:_____PHONE:_____
ADDRESS:_____CITY:_____
STATE:_____ZIP CODE:_____BIRTHDATE:_____ AGE: _____
INSURANCE COMPANY:_____INSURANCE #:_____
MEDICAID RECIPIENT ID#:_____

CIRCLE ONE ANSWER FOR EACH QUESTION. FILL IN BLANKS WHERE INDICATED

Present Status: RETIRED _____ WORKING_____OTHER_____
If working, describe occupation_____
Do you think you have a hearing loss? YES NO
If yes, which ear(s) RIGHT LEFT BOTH
Do you have frequent or constant ringing/buzzing in ears? YES NO
Do you have unusual drainage frim your ears? YES NO
Do you have frequent or constant ear pain? YES NO
Have you ever had a prolonged high fever? YES NO
Does any member of your family have a hearing loss other than due to aging? YES NO
Do you have frequent dizziness? _____ YES NO
Do you have a history of job-related noise exposure YES NO
If you answered "YES" to either of the two previous questions, have consistently employed good ear protection during the noise exposure? YES NO
Do you have a visual impairment? YES NO
Have you had a hearing loss before? YES NO
Have answered "YES" where and when? _____
Have you had any severe head injuries? YES NO
Have you worn a hearing aid? YES NO
Make/Model/Setting/Earmold _____

List any previous surgeries and dates.

List any medications presently prescribed for you.

List any allergies.

What is your primary complaint or problem with your ear/hearing, hunting, etc. ?

APPENDIX D

Informed Consent Form

APPENDIX D

MICHIGAN STATE UNIVERSITY

DEPARTMENT OF AUDIOLOGY AND SPEECH SCIENCES
378 COMMUNICATION ARTS AND SCIENCES BUILDING

EAST LANSING • MICHIGAN • 48824-1212

Department of Audiology and Speech Sciences
Communication Arts and Sciences Building, Room 5
Michigan State University
East Lansing, MI 48824-1212

INFORMED CONSENT FORM

1. *I,* _____, *freely and voluntarily consent to serve as a subject in a scientific study of* _____ *conducted by* _____ *and other student assistants.*

2. *I understand that the purpose of the study is to determine the usefulness of several electrophysiologic potentials which may have clinical applicability.*

3. *I understand that I will not be exposed to any experimental conditions which constitute a threat to my hearing, nor to my physical or psychological well-being. I understand that in the unlikely event of injury resulting from research procedures, Michigan State University, its agents, and employees will assume that responsibility as required by law. Emergency medical treatment for injuries or illness is available where the injury or illness is incurred in the course of an experiment. I have been advised that I should look toward my own health insurance program for payment of said medical expenses. If there are any questions, please contact Dr. Ernest J. Moore at 353-8788.*

4. *I understand that data gathered from me for this experiment are confidential, that no information uniquely identified with me will be made available to other persons or agencies, and that any publication of the results of this study will maintain anonymity.*

5. *I engage in this study on my own free will, with payment to me for my personal time, but without implication of personal benefit from the experiment. I understand that I may cease participation in the study at any time without prejudice to me or my standing as a member of the MSU Community.*

6. *I have had the opportunity to ask questions about the nature and purpose of the study, and I have been provided with a copy of this written informed consent form. I understand that upon completion of the study, and at my request, I can obtain additional explanation about the study.*

DATE: _____ SIGNED: _____
Participant

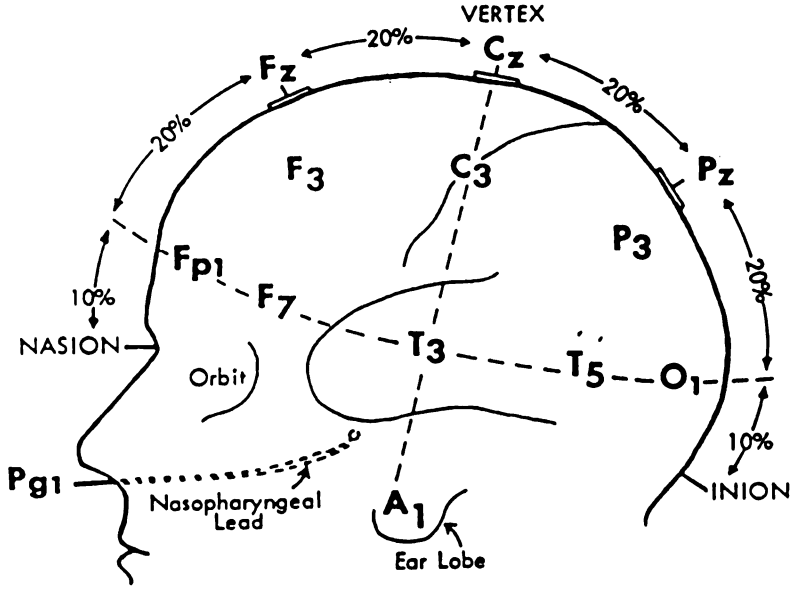
SIGNED: _____
Witness

APPENDIX E

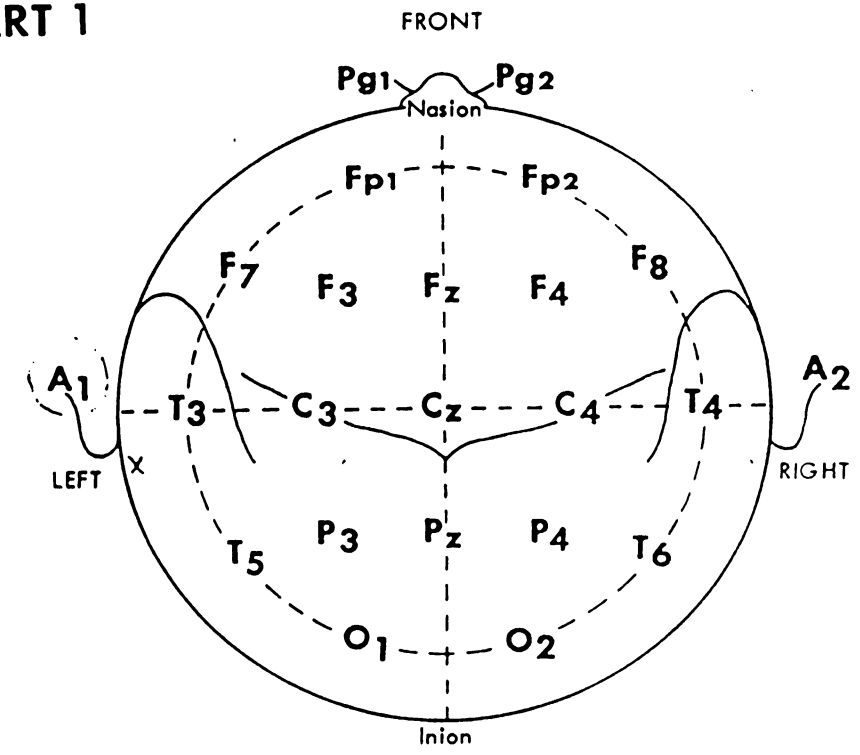
International (10-20) Electrode Placement

INTERNATIONAL (10-20) ELECTRODE PLACEMENT

CHART 1



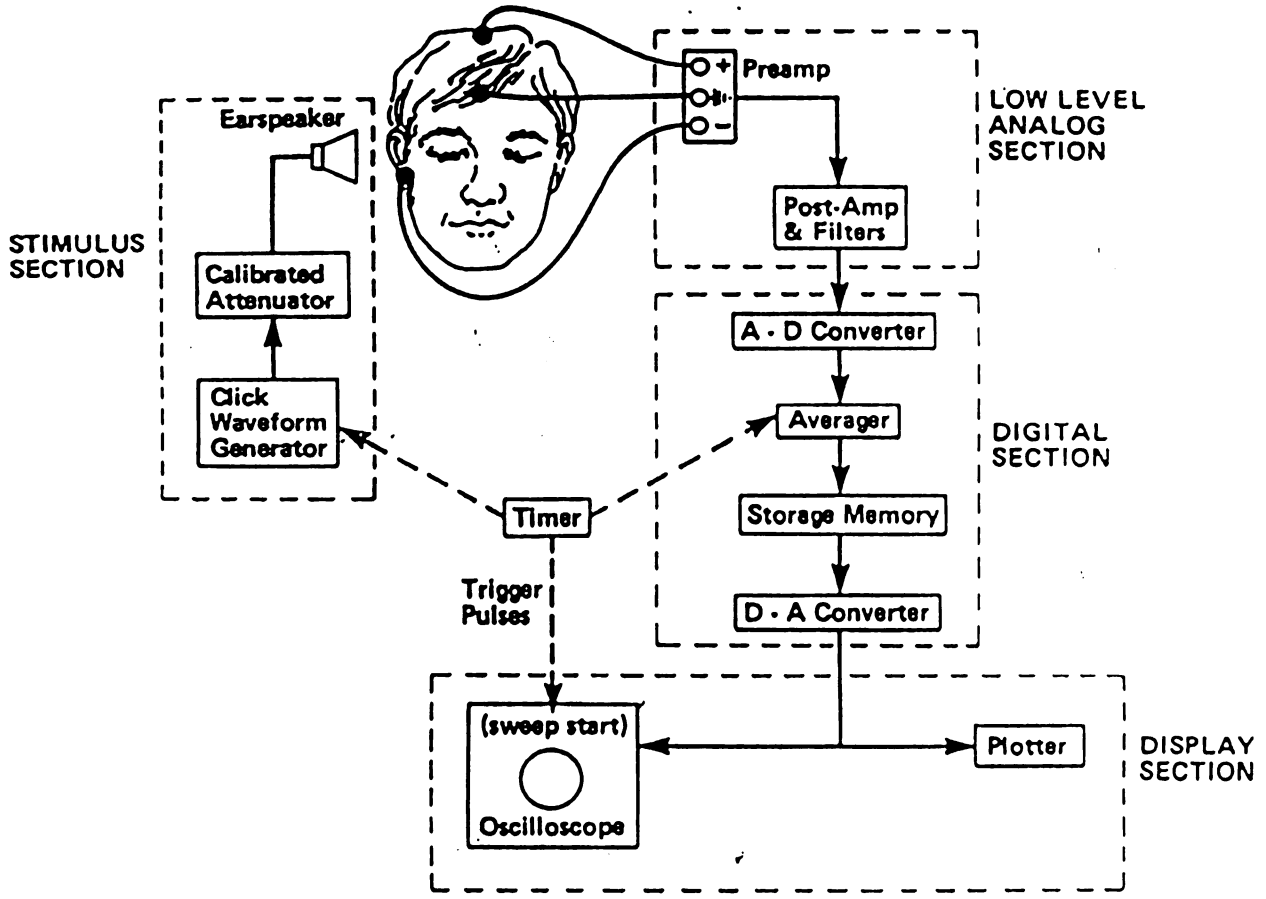
LEFT SIDE OF HEAD



TOP OF HEAD

APPENDIX F

Block Diagram of Averaging System for Recording Auditory Evoked Potentials.



Block diagram of averaging system for recording auditory evoked potentials. A-D = analog to digital; D-A = digital to analog.

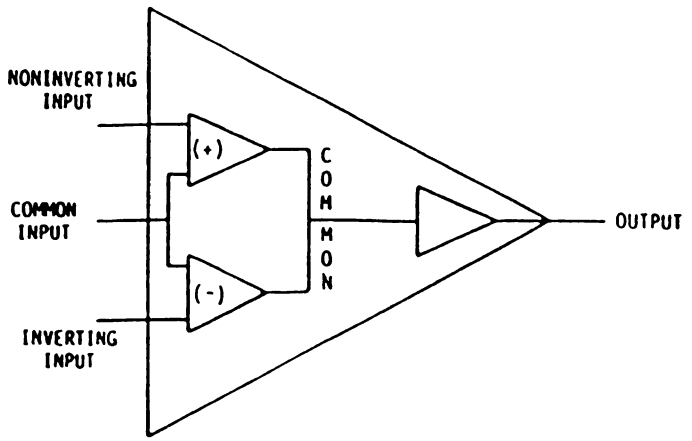
APPENDIX G

Top Panel: Schematic Illustration of a Differential Preamplifier.

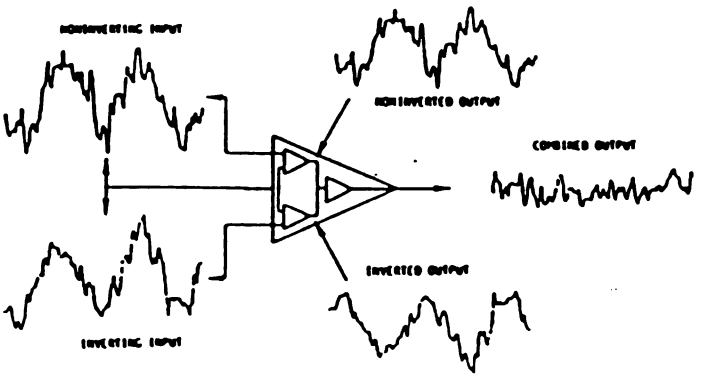
Middle Panel: Schematic Illustration of Noise Effects of a Preamplifier.

Bottom Panel: Examples of the ABR Detected at the Vertex and Mastoid Sites, and the Combination Effects of the Differential Preamplifier. The Common Electrode was Placed on the Forehead and is not Illustrated.

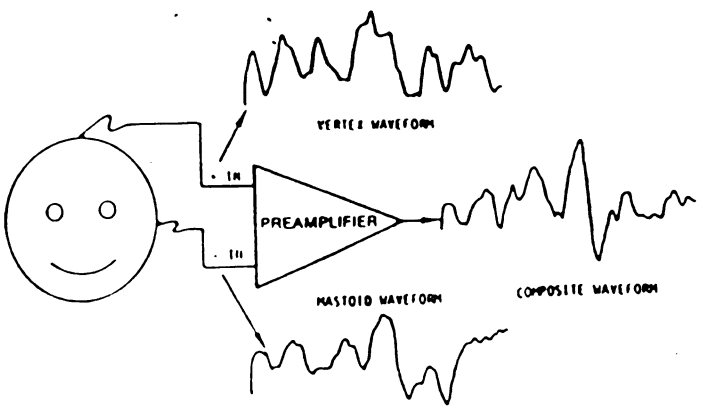
APPENDIX G



Schematic illustration of a differential preamplifier.



Schematic illustration of noise cancellation effects of a differential preampli-



Examples of the ABR detected at the vertex and mastoid sites, and the combination effects of the differential preamplifier. The common electrode was placed on the forehead and is not illustrated.

APPENDIX H

Effects of Intensity and Polarity on Latency of the BAEP. Analysis of Variance Results.

APPENDIX H

EFFECTS OF INTENSITY AND POLARITY ON LATENCY OF THE BAEP. ANALYSIS OF VARIANCE RESULTS.

WAVE I'

SOURCE	DF	SS	MS	F	P
Int	2	3.70287	1.85143	36.12	0.000
Pol	2	0.14068	0.07034	1.37	0.257
Int*Pol	4	0.11144	0.02786	0.54	0.704
Error	135	6.91919	0.05125		
Total	143	10.87418			

WAVE I

SOURCE	DF	SS	MS	F	P
Int	2	8.0136	4.0068	53.61	0.000
Pol	2	0.0123	0.0061	0.08	0.921
Int*Pol	4	0.0503	0.0126	0.17	0.954
Error	135	10.0901	0.0747		
Total	143	18.1662			

WAVE III

SOURCE	DF	SS	MS	F	P
Int	2	6.9139	3.4570	23.56	0.000
Pol	2	0.0268	0.0134	0.09	0.913
Int*Pol	4	0.1795	0.0449	0.31	0.874
Error	135	19.8120	0.1468		
Total	143	26.9322			

APPENDIX I

Effects of Intensity and Polarity on Amplitude of the BAEP. Analysis of Variance Results.

APPENDIX I

EFFECTS OF INTENSITY AND POLARITY ON AMPLITUDE OF THE BAEP. ANALYSIS OF VARIANCE RESULTS.

WAVE I'

SOURCE	DF	SS	MS	F	P
Int	2	5078.91	2539.45	159.64	0.000
Pol	2	458.26	229.13	14.40	0.000
Int*Pol	4	392.62	98.15	6.17	0.000
Error	63	1002.18	15.91		
Total	71	6931.97			

WAVE I

SOURCE	DF	SS	MS	F	P
Int	2	18035.5	9017.8	177.17	0.000
Pol	2	5431.8	2715.9	53.36	0.000
Int*Pol	4	6033.6	1508.4	29.63	0.000
Error	63	3206.7	50.9		
Total	71	32707.6			

WAVE III

SOURCE	DF	SS	MS	F	P
Int	2	3254.9	1627.5	58.13	0.000
Pol	2	2528.2	1264.2	45.15	0.000
Int*Pol	4	3957.1	989.3	35.34	0.000
Error	63	1763.7	28.0		
Total	71	11504.0			

WAVE V

SOURCE	DF	SS	MS	F	P
Int	2	22821.1	11410.5	195.78	0.000
Pol	2	1002.2	501.1	8.60	0.000
Int*Pol	4	1523.8	381.0	6.54	0.000
Error	63	3671.8	58.3		
Total	71	29018.9			

APPENDIX J

Effects of Intensity, Tone, and Polarity on Waves I′, I, III, and V Latencies of the BAEP. Analysis of Variance Results.

APPENDIX J

MTB > ANOVA LAT=INT;TONE;POL

Factor	Type	Levels	Values		
INT	fixed	3	50	60	70
TONE	fixed	3	1	2	3
POL	fixed	2	2	3	

Analysis of Variance for LAT

Source	DF	SS	MS	F	P
INT	2	8.24108	4.12054	49.45	0.000
TONE	2	1.64848	0.82424	9.89	0.000
POL	1	0.11236	0.11236	1.35	0.249
INT*TONE	4	2.34131	0.58533	7.03	0.000
INT*POL	2	2.06232	1.03116	12.38	0.000
TONE*POL	2	1.34754	0.67377	8.09	0.001
INT*TONE*POL	4	0.62180	0.15545	1.87	0.126
Error	72	5.99904	0.08332		
Total	89	22.37393			

MTB > WAVE I' LATENCY RESPONSES TO TONEBURST

MTB > ANOVA LAT=INT;TONE;POL

Factor	Type	Levels	Values		
INT	fixed	3	50	60	70
TONE	fixed	3	1	2	3
POL	fixed	2	2	3	

Analysis of Variance for LAT

Source	DF	SS	MS	F	P
INT	2	10.4482	5.2241	37.84	0.000
TONE	2	3.9433	1.9716	14.28	0.000
POL	1	0.0105	0.0105	0.08	0.784
INT*TONE	4	0.8848	0.2212	1.60	0.183
INT*POL	2	2.5362	1.2681	9.18	0.000
TONE*POL	2	0.1669	0.0835	0.60	0.549
INT*TONE*POL	4	2.3340	0.5835	4.23	0.004
Error	72	9.9412	0.1381		
Total	89	30.2650			

MTB > WAVE I LATENCY RESPONSES TO TONEBURST

MTB > ANOVA LAT=INT;TONE;POL

Factor	Type	Levels	Values		
INT	fixed	3	50	60	70
TONE	fixed	3	1	2	3
POL	fixed	2	2	3	

Analysis of Variance for LAT

Source	DF	SS	MS	F	P
INT	2	16.2326	8.1163	57.59	0.000
TONE	2	10.1132	5.0566	35.88	0.000
POL	1	0.0348	0.0348	0.25	0.621
INT*TONE	4	0.7550	0.1888	1.34	0.264
INT*POL	2	0.4702	0.2351	1.67	0.196
TONE*POL	2	2.0524	1.0262	7.28	0.001
INT*TONE*POL	4	1.6335	0.4084	2.90	0.028
Error	72	10.1471	0.1409		
Total	89	41.4388			

MTB > WAVE III LATENCY RESPONSES TO TONEBURST

MTB > ANOVA LAT=INT;TONE;POL

Factor	Type	Levels	Values		
INT	fixed	3	50	60	70
TONE	fixed	3	1	2	3
POL	fixed	2	2	3	

Analysis of Variance for LAT

Source	DF	SS	MS	F	P
INT	2	18.8963	9.4482	58.33	0.000
TONE	2	11.7669	5.8835	36.33	0.000
POL	1	0.0034	0.0034	0.02	0.886
INT*TONE	4	1.3084	0.3271	2.02	0.101
INT*POL	2	1.5122	0.7561	4.67	0.012
TONE*POL	2	0.7565	0.3783	2.34	0.104
INT*TONE*POL	4	1.7856	0.4464	2.76	0.034
Error	72	11.6615	0.1620		
Total	89	47.6908			

MTB > WAVE V LATENCY RESPONSES TO TONEBURST

APPENDIX K

Effects of Intensity, Tone, and Polarity on Waves I', I, III, and V on Amplitude of the BAEP. Analysis of Variance Results.

APPENDIX I

MTB > ANOVA AMPL0=INT;TONE;POL

Factor	Type	Levels	Values		
INT	fixed	3	50	60	70
TONE	fixed	3	1	2	3
POL	fixed	2	2	3	

Analysis of Variance for AMPL0

Source	DF	SS	MS	F	P
INT	2	1439.48	719.74	22.46	0.000
TONE	2	84.20	42.10	1.31	0.275
POL	1	329.25	329.25	10.28	0.002
INT*TONE	4	303.15	75.79	2.37	0.061
INT*POL	2	216.19	108.09	3.37	0.040
TONE*POL	2	338.24	169.12	5.28	0.007
INT*TONE*POL	4	111.14	27.78	0.87	0.488
Error	72	2306.87	32.04		
Total	89	5128.50			

MTB > ANOVA AMPL1=INT;TONE;POL

Factor	Type	Levels	Values		
INT	fixed	3	50	60	70
TONE	fixed	3	1	2	3
POL	fixed	2	2	3	

Analysis of Variance for AMPL1

Source	DF	SS	MS	F	P
INT	2	10429.76	5214.88	63.88	0.000
TONE	2	1947.84	973.92	11.93	0.000
POL	1	476.42	476.42	5.84	0.018
INT*TONE	4	2052.58	513.14	6.29	0.000
INT*POL	2	295.23	147.62	1.81	0.171
TONE*POL	2	22.99	11.50	0.14	0.869
INT*TONE*POL	4	721.68	180.42	2.21	0.076
Error	72	5878.14	81.64		
Total	89	21824.64			

MTB > ANOVA AMPL3=INT;TONE;POL

Factor	Type	Levels	Values		
INT	fixed	3	50	60	70
TONE	fixed	3	1	2	3
POL	fixed	2	2	3	

Analysis of Variance for AMPL3

Source	DF	SS	MS	F	P
INT	2	7389.9	3695.0	51.94	0.000
TONE	2	8255.6	4127.8	58.03	0.000
POL	1	2243.8	2243.8	31.54	0.000
INT*TONE	4	817.0	204.2	2.87	0.029
INT*POL	2	274.5	137.2	1.93	0.153
TONE*POL	2	3914.2	1957.1	27.51	0.000
INT*TONE*POL	4	1723.0	430.8	6.05	0.000
Error	72	5121.7	71.1		
Total	89	29739.6			

MTB > ANOVA AMPLV=INT;TONE;POL

Factor	Type	Levels	Values		
INT	fixed	3	50	60	70
TONE	fixed	3	1	2	3
POL	fixed	2	2	3	

Analysis of Variance for AMPLV

Source	DF	SS	MS	F	P
INT	2	11203.4	5601.7	85.48	0.000
TONE	2	16648.9	8324.5	127.03	0.000
POL	1	806.5	806.5	12.31	0.001
INT*TONE	4	907.7	226.9	3.46	0.012
INT*POL	2	74.1	37.1	0.57	0.570
TONE*POL	2	168.0	84.0	1.28	0.284
INT*TONE*POL	4	310.1	77.5	1.18	0.326
Error	72	4716.2	65.5		
Total	89	34837.0			

APPENDIX L

Delta-T Effects on Waves I', I, III, and V Latencies of the BAEP. Analysis of Variance Results.

APPENDIX L

MTB > ANOVA LATE00=DELTA|POL

Factor	Type	Levels	Values				
DELTA	fixed	5	10	50	100	200	400
POL	fixed	2	2	3			

Analysis of Variance for LATE00

Source	DF	SS	MS	F	P
DELTA	4	0.09915	0.02479	0.67	0.619
POL	1	0.12301	0.12301	3.31	0.077
DELTA*POL	4	0.07947	0.01987	0.53	0.712
Error	40	1.48832	0.03721		
Total	49	1.78995			

MTB > WAVE I' LATENCY RESPONSES TO DELTA-T

MTB > ANOVA LATE5=DELTA|POL

Factor	Type	Levels	Values				
DELTA	fixed	5	10	50	100	200	400
POL	fixed	2	2	3			

Analysis of Variance for LATE5

Source	DF	SS	MS	F	P
DELTA	4	0.02991	0.00748	0.19	0.943
POL	1	0.04322	0.04322	1.09	0.304
DELTA*POL	4	0.09439	0.02360	0.59	0.670
Error	40	1.59172	0.03979		
Total	49	1.75924			

MTB > WAVE V LATENCY RESPONSES TO DELTA-T

MTB > ANOVA LATI=DELTA|POL

Factor	Type	Levels	Values				
DELTA	fixed	5	10	50	100	200	400
POL	fixed	2	2	3			

Analysis of Variance for LATI

Source	DF	SS	MS	F	P
DELTA	4	0.04979	0.01245	0.34	0.852
POL	1	0.00029	0.00029	0.01	0.930
DELTA*POL	4	0.13533	0.03383	0.91	0.466
Error	40	1.48244	0.03706		
Total	49	1.66785			

MTB > WAVE I LATENCY RESPONSES TO DELTA-T

MTB > ANOVA LATE3=DELTA|POL

Factor	Type	Levels	Values				
DELTA	fixed	5	10	50	100	200	400
POL	fixed	2	2	3			

Analysis of Variance for LATE3

Source	DF	SS	MS	F	P
DELTA	4	0.01935	0.00484	0.13	0.972
POL	1	0.06266	0.06266	1.65	0.207
DELTA*POL	4	0.10057	0.02514	0.66	0.623
Error	40	1.52164	0.03804		
Total	49	1.70422			

MTB > WAVE III LATENCY RESPONSES TO DELTA

APPENDIX M

Delta-T Effects on Waves I′, I, III, and V Amplitude of the BAEP. Analysis of Variance Results.

APPENDIX H

MTB > ANOVA AMPL0=DELTA|POL

Factor	Type	Levels	Values				
DELTA	fixed	5	10	50	100	200	400
POL	fixed	2	2	3			

Analysis of Variance for AMPL0

Source	DF	SS	MS	F	P
DELTA	4	877.2	219.3	0.70	0.598
POL	1	1230.8	1230.8	3.91	0.055
DELTA*POL	4	471.1	117.8	0.37	0.825
Error	40	12578.8	314.5		
Total	49	15157.9			

MTB > WAVE I AMPLITUDE RESPONSES TO DELTA-T

MTB > ANOVA AMPL3=DELTA|POL

Factor	Type	Levels	Values				
DELTA	fixed	5	10	50	100	200	400
POL	fixed	2	2	3			

Analysis of Variance for AMPL3

Source	DF	SS	MS	F	P
DELTA	4	110643	27661	1.87	0.134
POL	1	12016	12016	0.81	0.372
DELTA*POL	4	59264	14816	1.00	0.417
Error	40	590259	14756		
Total	49	772182			

MTB > WAVE III AMPLITUDE RESPONSES TO DELTA-T

MTB > ANOVA AMPLI=DELTA|POL

Factor	Type	Levels	Values				
DELTA	fixed	5	10	50	100	200	400
POL	fixed	2	2	3			

Analysis of Variance for AMPLI

Source	DF	SS	MS	F	P
DELTA	4	5477	1369	0.68	0.608
POL	1	2438	2438	1.22	0.277
DELTA*POL	4	3564	891	0.44	0.776
Error	40	80166	2004		
Total	49	91645			

MTB > WAVE I AMPLITUDE RESPONSES TO DELTA-T

MTB > ANOVA AMPL5=DELTA|POL

Factor	Type	Levels	Values				
DELTA	fixed	5	10	50	100	200	400
POL	fixed	2	2	3			

Analysis of Variance for AMPL5

Source	DF	SS	MS	F	P
DELTA	4	67561	16890	0.43	0.783
POL	1	35717	35717	0.92	0.344
DELTA*POL	4	105099	26275	0.68	0.613
Error	40	1556999	38925		
Total	49	1765376			

MTB > WAVE V AMPLITUDE RESPONSES TO DELTA-T

APPENDIX N

Repetition Rate Effects on Waves I′, I, and III Latencies of the BAEP. Analysis of Variance Results.

APPENDIX N

MTB > ANOVA LAT0=REPR;POL

Factor	Type	Levels	Values		
REPR	fixed	3	3	10	96
POL	fixed	2	2	3	

Analysis of Variance for LAT0

Source	DF	SS	MS	F	P
REPR	2	0.35059	0.17529	10.67	0.000
POL	1	0.30000	0.30000	18.26	0.000
REPR*POL	2	0.07352	0.03676	2.24	0.128
Error	24	0.39424	0.01643		
Total	29	1.11835			

MTB > WAVE I' RESPONSES TO REPETITION RATES

MTB > ANOVA LATE1=REPR;POL

Factor	Type	Levels	Values		
REPR	fixed	3	3	10	96
POL	fixed	2	2	3	

Analysis of Variance for LATE1

Source	DF	SS	MS	F	P
REPR	2	0.014587	0.007293	1.16	0.330
POL	1	0.158413	0.158413	25.20	0.000
REPR*POL	2	0.000987	0.000493	0.08	0.925
Error	24	0.150880	0.006287		
Total	29	0.324867			

MTB > WAVE I LATENCY RESPONSES TO REPETITION RATES

MTB > ANOVA LATE3=REPR;POL

Factor	Type	Levels	Values		
REPR	fixed	3	3	10	96
POL	fixed	2	2	3	

Analysis of Variance for LATE3

Source	DF	SS	MS	F	P
REPR	2	1.65715	0.82857	25.39	0.000
POL	1	0.34992	0.34992	10.72	0.003
REPR*POL	2	0.10568	0.05284	1.62	0.219
Error	24	0.78320	0.03263		
Total	29	2.89595			

MTB > WAVE III LATENCY RESPONSES TO REPETITION RATES

APPENDIX O

Repetition Rate Effects on Waves I', I, and III Amplitudes of the BAEP. Analysis of Variance Results.

APPENDIX O

MTB > ANOVA AMPLO=REPR|POL

Factor	Type	Levels	Values		
REPR	fixed	3	3	10	96
POL	fixed	2	2	3	

Analysis of Variance for AMPLO

Source	DF	SS	MS	F	P
REPR	2	377.39	188.70	3.48	0.047
POL	1	945.73	945.73	17.43	0.000
REPR*POL	2	34.01	17.00	0.31	0.734
Error	24	1302.31	54.26		
Total	29	2659.44			

MTB > WAVE I AMPLITUDE RESPONSES TO 3.22, 10.21, AND 96.00 REPR

Factor	Type	Levels	Values		
REPR	fixed	3	3	10	96
POL	fixed	2	2	3	

Analysis of Variance for AMPLI

Source	DF	SS	MS	F	P
REPR	2	35570.8	17785.4	49.06	0.000
POL	1	792.0	792.0	2.18	0.152
REPR*POL	2	3578.6	1789.3	4.94	0.016
Error	24	8701.3	362.6		
Total	29	48642.8			

MTB > WAVE I AMPLITUDE RESPONSES TO REPETITION RATES

MTB > ANOVA AMPL3=REPR|POL

Factor	Type	Levels	Values		
REPR	fixed	3	3	10	96
POL	fixed	2	2	3	

Analysis of Variance for AMPL3

Source	DF	SS	MS	F	P
REPR	2	15401.3	7700.7	81.94	0.000
POL	1	2652.9	2652.9	28.23	0.000
REPR*POL	2	2987.8	1493.9	15.90	0.000
Error	24	2255.5	94.0		
Total	29	23297.5			

MTB > WAVE III AMPLITUDE RESPONSES TO REPETITION RATES

REFERENCES

REFERENCES

Allen, J.A., (1980). Managing Teenage Pregnancy. New York: Praeger Publishers.

Allison, T., Wood, C.C., & Goff, W.R., (1983). Brain stem auditory, pattern-reversal visual, and short-latency somatosensory evoked potentials: Latencies in relation to age, sex, and brain body size. Electroencephalography and Clinical Neurophysiology, 55, 619-636.

Amedofu, G.K.P., (1985). Augmenting and reducing brain stem evoked measurements among individuals. Unpublished masters thesis. Michigan State University, East Lansing, MI.

Ananthanarayan, A.K., & Gerken, G.M., (1987). Response enhancement and reduction of the auditory brain-stem response in a forward-masking paradigm. Electroencephalography and Clinical Neurophysiology, 66, 427-439.

Ananthanarayan, A.K., & Gerken, G.M., (1983). Post-stimulatory effects on the auditory brain stem response: partial-masking and enhancement. Electroencephalography and Clinical Neurophysiology, 55, 223-226.

Asante, K.O., (1988). The Importance of Fetal Alcohol Syndrome in the Handicapped Population. In G.C. Robinson & R.W. Armstrong (Eds.). Alcohol and child/family health (pp. 123-134) Vancouver, British Columbia, British Columbia Fetal Alcohol Syndrome.

Bauch, C.D., Rose, D.E., & Harner, S.G., (1980). Brain stem responses to tone pip and click stimuli. Ear Hear, 1, 181-184.

Beagley, H.A., & Sheldrake, J., (1978). Differences in brainstem response latency with age and sex. British Journal of Audiology, 12, 69-77.

Benito, M., Falco, G., & Lauro, A., (1984). Brain stem evoked potentials. Description of the "O" wave of possible electro-cochlear. Electroencephalography Clinical Neurophysiology, 58, 100.

Borg, E., & Lofquist, L., (1982). Auditory brainstem response to rarefaction and condensation clicks in normal ears. Scand Audiol, 11, 227-235.

Boston, J.R., & Ainslie, P.J., (1980). Effects of analog and digital filtering on brain stem auditory evoked potentials. Electro-encephalography and Clinical Neurophysiology 48, 361-364.

Boudreau, J.C., (1965a). Stimulus correlates of wave activity in the superior-olivary of the cat. J. Acoust. Soc. Am., 37, 779-785.

Boudreau, J.C., (1965b). Neural volleying: Upper frequency limits detectable in the auditory system. Nature, 208, 1237-1238.

Buchwald, J., & Huang, Ch., (1975). Far-field acoustic response: Origins in the cat. Science, 189, 382-384.

Cacace, A.T., Shy, M., & Satya-Murta, S., (1980). Effects of Brainstem auditory evoked potentials: A comparison of two high-frequency filter settings. Neurology, 30, 765-767.

Carterette, E.C., (1956). Loudness adaptation for bands of noise. J. Acoust. Soc. Am, 28(5), 865-871.

Carterette, E.C., (1955). Perstimulatory auditory fatigue for continuous and interrupted noise. J. Acous. Soc. Am., 27, 103-111.

Chiappa, K.H., (1983). Evoked potentials in clinical medicine (chapters 1, 4, and 5). New York: Raven Press.

Chiappa, K.H., Gladstone, K.J., & Young, R.R., (1979). Brainstem auditory evoked responses; Studies of waveform variations in 50 normal human subjects. Archives of Neurology, 36, 81-87.

Coats, A.C., (1983). Instrumentation. In E.J. Moore (Ed.), Bases of auditory brain-stem evoked responses (Chapter 8). New York: Grune and Stratton.

Coats, A.C., (1974). On electrocochleographic electrode design. J. Acoust. Soc. Am., 56, 708-711.

Coats, A.C., (1971). Depression of click action potential by attenuation, cooling, and masking. Acta Oto-laryngol Suppl., 284, 1-19.

Coats, A.C., (1967). Physiological masking in the peripheral auditory system. III. Effect of varying test-click intensity. Journal of Neurophysiology, 30(5), 931-948.

Coats, A.C., (1964a). Physiological observations of auditory masking. I. Effect of masking duration. Journal of Neurophysiology, 27, 989-1000.

Coats, A.C., (1964b). Physiological observations of auditory masking. II. Effect of masking duration. Journal of Neurophysiology, 27, 1001-1010.

Cohn, L.F., & Koushki, P.A., (1991). Social attitude and traffic noise: A study in Riyadh, Saudi Arabia. Journal of Urban Affairs, 13(2), 233-242.

Daly, D.M., Roeser, R.J., Aung, M.H., & Daly, D.D., (1977). Early evoked potentials in patients with acoustic neuroma. Electoencephalography and Clinical Neurophysiology, 43, 151-159.

Davis, H., (1976). Principles of electric response audiometry. Ann. Otol. Rhinol. Laryngology, 85(Suppl 28), 1-96.

Davis, H., & Hirsh, S. K., (1976) The audiometric utility of brain stem responses to low-frequency sounds. Audiology, 15, 181-195.

Davis, H., Morgan, C.T., Hawkins, J.E., Galambos, R., & Smith, F.W., (1950). Temporary deafness following exposure to loud tones & noise. Acta Otolaryngologica Supplement, 88, 1-87.

Derbyshire, A.J., & Davis, H., (1935). The action potentials of the auditory nerve. American Journal of Physiology, 113, 476-504.

DeRosier, D.J., Tilney, J.L., & Flicker, P., (1980). A change in the twist of actin-containing filaments occurs during the extension of the acrosomal process in Limulus sperm. J. Cell Biol, 73, 375-389.

Dolan, D.F., Xi, L., & Nuttall, A.L., (1989). Characteristics of an EPSP-like potential recorded from the round. J. Acoust. Soc. Am., 86(6), 2167-2171.

Dolan, T.G., & Klein, A.J., (1987). Effect of signal temporal shaping on the frequency specificity of the action in gerbils. Audiology, 26, 20-30.

Don, M., Allen, A.R., & Starr, A., (1977). Effect of click rate on the latency of auditory brain stem responses in humans. Annals of Otolaryngology, 86, 186-195.

Drenckhahn, D., Kellner, J., Mannherz, H.G., Groschel-Steward, U., Kendrick-Jones, J., & Scholey, J., (1982). Absence of myosin-like immuno-reactivity in stereocilia of cochlear hair cells. Nature, 300, 531-532.

Durrant, J.D., (1983). Fundamentals of Sound Generation. In E.J. Moore (Ed.), Bases of Auditory brain-stem responses (Chapter 3). New York: Grune and Stratton.

Eccles, J.C., (1969). Excitatory and inhibitory mechanisms in brain. In H.H. Jasper, A.A. Ward, & A. Pope, (Eds.), Basic mechanisms of the epilepsies Boston: Little Brown and Co.

Eccles, J.C., (1966). The ionic mechanisms of excitatory and inhibitory synaptic action. Ann. New York Acad. Science., 137, 473.

Eggermont, J.J., & Don, M., (1982). Analysis of click-evoked brainstem auditory electric potentials using high-pass noise masking and its clinical application. Annals New York Academy of Sciences, 471-486.

Eggermont, J.J., & Don, M., (1980). Analysis of the click-evoked brainstem potentials in humans using high-pass noise masking. II. Effect of click intensity. J. Acoust. Soc. Am., 68(6), 1671-1675.

Eggermont, J.J., & Spoor, A., (1973a). Cochlear adaptation in guinea pigs: A quantitative description. Audiology, 12, 193-220.

Eggermont, J.J., & Spoor, A., (1973b). Masking of action potentials in the guinea pig cochlea, its relation to adaptation. Audiology, 12, 221-241.

Eisenberg, R.B., (1965). Auditory behavior in the human neonate. I. Methodologic problems and the logical design of research procedures. J. Audiology Research, 5, 159-177.

Elberling, C., (1979). Auditory electrophysiology: Spectral analysis of cochlear and brainstem evoked potentials. Scand. Audiology, 8, 57-64.

Elberling, C., (1976). Action potentials recorded from the promontory and the surface compared with the recordings from the ear canal in man. Scandinavian Audiology, 5, 69-78.

Elliot, L.L., (1962). Backward and forward masking of probe tones of different frequencies. J. Acoust. Soc. Am., 34, 1116-1117.

Evans, E.F., & Wilson, J.P., (1973). The frequency selectivity of the cochlea. In A. Moller; (Ed.). Basic mechanisms in hearing (519-554). New York: Academic Press.

Fabiani, M., Sohmer, H., Tait, C., Garni, M., & Kinarti, R., (1979). A functional measure of brain activity: Brain stem transmission time. Electroencephalography and Clinical Neurophysiology, 47, 483-491.

Finck, A., (1966). Physiological correlate of tonal masking. J. Acoust. Soc. Am., 39, 1056-1062.

Finitzo-Hieber, T., Hecox, K., & Cone, B., (1979). Brain stem auditory evoked potentials in patients with congenital atresia. Laryngoscope, 89, 1151-1158.

Franklin, D.L., (1987). Black Adolescent Pregnancy: A Literature Review. In S.F. Battle (Ed.) The black adolescent parent (pp. 15-39).

Gardner, M.B., (1947). Short duration auditory fatigue a method of classifying hearing impairment. J. Acoust. Soc. Am., 19, 178-190. New York: The Haworth Press.

Gennser, G., Marsal, K., & Brantmark, B., (1975). Maternal smoking and fetal breathing movements. Am. J. Obstet. Gynecol. 123 861.

Gerling, I.J., & Finitzo-Hieber, T., (1983). Auditory brainstem response with high stimulus rates in normal and patient populations. Annals of Otology, Rhinology, and Laryngology, 92, 119-123.

Gisselsson, & Sorensen, (1959). Auditory adaptation and fatigue in cochlear potentials. Acta Otolaryngologica, 50, 438-450.

Glasscock III, M.E., Jackson, C.G., & Josey, A.F., (1987). The ABR handbook: Auditory brainstem response (2nd. ed.) N.Y.: Thieme Medical Publishers, Inc.

Harris, D.M., & Dallos, P., (1979). Forward masking of auditory nerve fiber responses. J. Neurophysiology, 42(4), 1083-1107.

Hecox, K., Squires, N., & Galambos, R., (1976). Brainstem auditory evoked responses in man. Effect of stimulus rise-time and duration. J. Accoust. Soc. Am., 60, 1187-1192.

Hecox, K., & Galambos, R., (1974). Brainstem evoked auditory responses in human infants and adults. Arch. Otolaryngology, 99, 30-34.

Henrman, E., Somjen, G., & Carpenter, D.O., (1965a). Functional significance of cell size in spinal motoneurons. J. Neurophysiol, 28, 560.

Henrman, E., Somjen, G., & Carpenter, D.O., (1965b). Excitability and inhibitability of motoneurons of different sizes. J. Neurophysiol, 28, 599.

Hood, J.D., (1950). Studies in auditory fatigue and adaptation. Acta Otolarygologica Supplement, 92, 1-57.

Hoshino, T., (1976). Attachment of inner sensory hair cells to tectorial membrane. A scanning electron microscopic study. Otology Rhinology and Laryngology, 38, 11-18.

Hughes, J.R., Fino, J., & Gagnon, L., (1981). "The importance of phase of stimulus and the reference recording electrode in brain stem auditory evoked potentials," Electroencephalography and Clinical Neurophysiology, 51, 611-623.

Hughes, J.R., & Fino, J., (1980). Usefulness of piezoelectric earphones in recording of the brain stem auditory potentials: A new early deflection. Electroencephalograph Clinical Neurophysiology, 48, 357-360.

Hughson, W., & Witting, E.G., (1934). An objective study of auditory fatigue. Acta Otolaryngol, 21, 457-486.

Hyde. M.L., Stephens, S.D.G., & Thornton, A.R.D., (1976). Stimulus repetition rate and the early brainstem responses. British Journal of Audiology, 10, 41-50.

Iurato, S., (1974). Efferent innervation of the cochlea. In W.D. Keidel, & W.D. Neff, (Eds.). Auditory system, anatomy-physiology (ear) Handbook of sensory physiology Vol. V/1 Springer Verlag, Berlin. pp. 261-282.

Jasper, H.H., (1958). 'Report of the committee of methods of clinical examination in electroencephalography,' Electroecephalography and Clinical Neurophysiology, 10, 370.

Jerger, J., (1956). Recovery pattern from auditory fatigue. J. Speech and Hearing Disorders, 21(1), 39-46.

Jerger, J., & Hall, J., (1980). Effects of age and sex on auditory brainstem response. Archives of Otolaryngology, 106, 387-391.

Jewett, D.L., & Williston, J.S., (1971). Auditory-evoked far fields averaged from the scalp of humans. Brain, 94, 681-696.

Jewett, D.L., Romano, M.N., & Williston, J.S., (1970). Human auditory evoked potentials: possible brain stem components detected on the scalp. Science, 167, 1517-1518.

Jones, K.L., & Smith, D.W., (1973). Recognition of the fetal alcohol syndrome in infancy. Lancet 2, 999-1001.

Jones, K.L., Smith, D.W., Ulleland, C.N., & Streissguth, A.P., (1973). Patterns of malformation inoffspring of alcoholic mothers. Lancet, 1, 1267-71.

Jorgensen, J.M., & Flock, A., (1976). Non-innervated sense organs of the lateral line: development in the regenerating tail of the salamander. Ambystoma mexicanum. J. Neurocytology, 5, 33-41.

Josey, A.F., (1985). Auditory Brainstem Response in Site of Lesion Testing. In J. Katz (Ed.), Handbook of clinical audiology (pp. 534-548) 3rd ed. Baltimore: William and Wilkins.

Kandel, E.R., (1977). Handbook of physiology: Section 1: The nervous system. Vol.I. Cellular Biology of Neurons, Parts 1 and 2, Bethesda, Maryland: American Physiological Society.

Kevanishvili, Z., & Aphonchenko, V., (1981). Click polarity inversion effects upon the human brainstem auditory potential. Scand Audiology, 10, 141-147.

Kevanishvili, Z., & Aphonchenko, V., (1979). Frequency composition of brain stem auditory evoked potentials. Scand. Audiology, 8, 51-55.

Khanna, S.M., & Leonard, D.G.B., (1982) Basilar membrane tuning in the cat cochlea. Science 215, 305-306.

Kiang, N.Y.S., Rho, J.M., Northrop, C.C., Liberman, M.C., & Ryugo, D.K., (1982) Hair-cell innervation by spiral ganglion cells in adult cats. Science 217, 175-177.

Kiang, N.Y.S., Watanabe, T., Thomas, E.C., & Clark, L.F., (1965). Discharge Patterns of Single Fibers in the Cat's Auditory Nerve. Res Monograph, 35, Cambridge, M.A.: M.I.T. Press.

Kim, D.O., & Molnar, C.E., (1975). Cochlear Mechanics: Measurements and Models. In D.B. Tower (Ed.). The nervous system Vol. 3 human communication and its disorders New York: Raven Press.

Kimura, R.S., (1966). Hair of the cochlear sensory cells and their attachment to the tectorial membrane. Acta. Otolaryngologica, (Stockh) 61, 55-72.

Kjaer, M., (1979). Differences if latencies and amplitudes of brain stem evoked potentials in subgroups of a normal material. Acta Neurologica Scandinavia, 59, 72-79.

Klinke, R., Caird, D.M., Lowenheim, H., & Moore, E.J., (1988). Beeinflubt ein intracochleares exzitatoricsches potential die hirnstammpotentiale? Arch. Oto-Rhino-Laryngol Suppl. 1988/II. 159-161.

Kodera, K., Marsh, R.R., Suzuki, M., Suzuki, J-I., (1983). Portions of tone pips contributing to frequency-selective auditory brain stem responses. Audiology, 22, 209-218.

Konkle, D.F., & Orchik, D.J., (1979). Auditory Adaptation. In W.F. Rintelmann (Ed.), Hearing assessment (pp. 207-233). Baltimore, MD: University Park Press.

Kupperman, R., (1971). Cochlea masking and adaptation. Acta Oto-laryngol, 71, 232-241.

Lang, J., (1981). Facial and vestibulocochlear nerve, topographic anatomy and variations. In M. Samii & P.J. Jannetta (Eds.), The cranial nerves. New York: Springer-Verlag.

Laukli, E., & Mair, I.W.S., (1981) Early auditory-evoked responses: Filter effects. Audiology, 20, 300-312.

Liberman, M.C., (1980a). Morphological differences among radial afferent fibers in the cat cochlea: an electron-microscopic study of serial sections. Hearing Research 3, 45-63.

Liberman, M.C., (1980b). Efferent synapses in the inner hair cell area of the cat cochlea: an electron-microscopic study of serial sections. Hearing Research 3, 189-204.

Lim, D.J., (1972). Fine morphology of the tectorial membrane. Its relationship to the organ of Corti. Arch. Otolaryngology, 96, 199-215.

Luscher, E., & Zwislocki, J., (1947). The decay of sensation and the remainder of adaptation after short pure-tone impulses on the ear. Acta Otolaryngologica, 35, 428-445.

Manning, F.A., & Feyerabend, C., (1976). Cigarette smoking and fetal breathing movements. British J. Obstet. 83, 262.

McGee, T.A., Ryan, A., & Dallos, P., (1976). Psychophysical tuning curves of chinchillas. J. Acoust. Soc. Am., 60, 1146-1150.

Mendel, M.I., & Goldstein, R., (1969). The effects of test conditions on the early components of the averaged electroencephalic response. J. Speech and Hearing Research, 12, 344-350.

Michalewski, H.J., Thompson, L.W., Patterson, J.V., Bowman, T.E., & Litzelman, D., (1980). Sex differences in the amplitudes and latencies of the human auditory brain stem potential. Electroencephalography and Clinical Neurophysiology, 48, 351-356.

Moller, M.B., & Moller, A.R.,(1985). Auditory Brainstem-Evoked Response (ABR) in Diagnosis of Eighth Nerve and Brainstem Lesions. In M.L. Pinheiro & F.E. Musiek (Eds.), Assessment of central dysfunction foundations and clinical correlates (chapter 4). Baltimore: Williams and Wilkins.

Moore, B.C., (1978). Psychophysical tuning curves measured in simultaneous and forward masking. J. Acoust. Soc. Am., 63, 524-532.

Moore, E.J., (1983). Effects of Stimulus Parameters. In E.J. Moore (Ed.), Bases of auditory brain-stem evoked responses (chapter 9). New York: Grune and Stratton.

Moore, E.J., Caird, D.M., Klinke, R., & Lowenheim, H., (1988). Effects of intracochlear infusion of TTX and GDEE on brain stem auditory evoked potentials. Association for Research in Otolaryngology. 31, St Petersburg, Beach, FL, January, 1988 26.

Moore, E.J., & Semela, J.J.M., (1985). The potential of the auditory brain-stem response: A neural response or systematic artifact? A paper presented to the XXII Workshop on Inner Ear Biology (Sept.) Wurzburg - West Germany.

Morrison, D., Schindler, R.A., & Wersall, J., (1975). A quantitative analysis of the afferent innervation of the organ of Corti in guinea pig. Acta. Otolaryngology, 79, 11-23.

Munson, W.A., & Gardner, M.B., (1950). Loudness patterns - a new approach. J. Acoust. Soc. Am., 22, 177-190.

Musiek, F.E., (1989). Essentials of the Auditory Brain-Stem Responses. A paper presented to at the Neuro-Audiology Seminar (April) Mercy Hospital, Savannah, Georgia.

Nadol, J.B. Jr., (1984). Incidence of reciprocal synapses on outer hair cells of the human organ of Corti. Ann. Otol. Rhinol. Laryngol. 93, 247-250.

Nadol, J.B. Jr., (1983a). Serial section reconstruction of the hair cells in the human organ of Corti. I. Inner hair cells. Laryngoscope, 93, 599-614.

Nadol, J.B. Jr., (1983b). Serial section reconstruction of the hair cells in the human organ of Corti. II. Inner hair cells. Laryngoscope 93, 780-791.

Nadol, J.B. Jr., (1981). Reciprocal synapses at the base of outer hair cells in the organ of Corti in man. Ann. Otol. Rhinol. Laryngol. 90, 12-17.

Naunton R. F., & Zerlin, S., (1976). Human whole-nerve response to clicks of various frequencies. Audiology, 15, 1-9.

Nuttall, A.L., (1986). Physiology of Hair Cells. In R.A. Altschuler, R.P. Bobbin & D.W. Hoffman, (Eds.), Neurobiology of hearing: the cochlea. (Chapter 3). New York: Raven Press.

Olphen, A.F. van, Rodenburg, M., & Verwey, C., (1979). Influence of stimulus repetition rate on acoustic stimulation on brain-stem-evoked responses in man. Audiology, 18, 388-394.

Ornitz, E.M., & Walter, D.O., (1975). The effect of sound pressure waveform on human brain stem evoked responses. Brain Research, 92, 490-498.

Ostrea, E.M., (1978). The Drug Dependent Woman During Pregnancy. In E.M. Ostrea, C.J. Chavez & J.C. Stryker (Eds.) The care of drug dependent pregnant woman and her infant. (pp. 23-41). Lansing, MI: Department of Public Health.

Paparella, M.M., & Jung, T.T.K., (1983). Disorders of the Auditory System. In E.J. Moore (Ed.), Bases of auditory brain-stem responses. (Chapter 5). New York: Grune and Stratton.

Peake, W.T., Kiang, N.Y.S., & Goldstein, M.H., (1962). Rate function for auditory nerve responses to bursts of noise: effects of changes in stimulus parameters. J. Acous. Soc. Am., 34, 571-575.

Perkins, R.E.; & Morest, D.K.; (1975). A study of cochlear innervation patterns in cats and rats with the Golgi method and Nomarski optics. J. Comp. Neurol. 163, 129-158.

Picton, T.W.; & Fitzgerald, P.G.; (1983). A General Description of the Human Auditory Evoked Potentials. In E.J. Moore (Ed.), Bases of auditory brain-stem evoked responses (Chapter 6). New York: Grune and Stratton.

Picton, T.W., Stapells, D.R., & Campbell, K.R., (1981). Auditory evoked potentials from the human cochlea and brainstem. J. Otol., 9(Supplement), 1-41.

Picton, T.W., Woods, A.B., Baribeau-Braun, J., & Healey, T.M.G., (1977) Evoked potential audiometry. The Journal Otolaryngology, 6, 90-119.

Pollack, I., (1952). The loudness of bands of noise. J. Acoust. Soc. Am., 24, 533-538.

Pollack, I., (1951). On measurement of the loudness of white noise. J. Acoust. Soc. Am., 23, 654-657.

Pratt, H., & Sohmer, H., (1976). Intensity and rate functions of cochlear and brainstem evoked responses to click stimulation in man. Archives of Otorhinolaryngology, 212, 85-92.

Pujol, R.; & Lenoir, M.; (1986) The four types of synapses in the organ of corti. In R.A. Altschuler; R.P. Bobbin; & D.W. Hoffman; (Eds.) Neurobiology of hearing: The cochlea (pp. 161-172) New York: Raven Press.

Rhode, W.S.; (1978). Some observations on cochlear mechanics. J. Acoust. Soc. Am., 64, 158-176.

Robinson, K., & Rudge, P., (1977). Abnormalities of the auditory evoked potential in patients with multiple sclerosis. Brain 100, 19-40.

Rosenhamer, H.J., Lindstrom, B., & Lundborg, J., (1978). On the use of click evoked electric brainstem responses in audiologic diagnosis. I. The variability of the normal response. Scand Audiol, 7, 193-206.

Ruth, R.A., Hildenbrand, D.L., & Cantrell, R.W., (1982). A study of methods used to enhance wave I in the auditory brain stem response. Otolaryngology and Head and Neck Surgery, 90, 635-640.

Saito, K., (1980). Fine structure of the sensory epithelium of the guinea pig organ of Corti: Afferent and efferent synapses of hair cells. J. Ultrastruct. Res. 71, 222-232.

Schmidt, R.F., (1983). In R.F. Schmidt, & G. Thews, (Eds.). Human physiology (Chapters 3 and 4). Berlin: Springer-Verlag.

Schwartz, D.A., & Berry, G.A., (1985). Normative Aspects of ABR. In J.T. Jacobson (Ed.), The auditory brainstem response (pp. 65-97). San Diego, California: College-Hill Press.

Simmons, F.B., & Beatty, D.L., (1962). The significance of round window recorded cochlear potentials in hearing. Annals of Otology Rhinology, and Laryngology, 71, 676-801.

Sininger, Y.S., & Don, M., (1989). Effects of click rate and electrode orientation on threshold of the auditory brainstem response. J. Speech and Hearing Research, 32(4), 880-886.

Skinner, P.H., (1978). Electroencephalic Response Audiometry. In J. Katz, (Ed.), Handbook of clinical audiology (2nd ed.). Baltimore MD: The Williams and Wilkins Company.

Small, A.M., (1963). Auditory Adaptation. In J. Jerger (Ed.), Modern developments in audiology (1st ed.) NY: Academic Press.

Small, A.M., (1959). Pure tone masking. J. Acoust. Soc. Am., 31, 1619-1625.

Smith, C.A., & Rasmussen, G.L., (1963). Recent observations on the olivo-cochlear bundle. Ann. Otol. Rhinol. Laryngol, 72, 489-497.

Snyder, R.L., & Schreiner, C.E., (1985). Forward masking of the auditory nerve neurophonic (ANN) and the frequency following response (FFR). Hearing Research, 20, 45-62.

Sobkowicz, H.M., Rose, J.E.; Scott, G.E., & Slapnick, S.M., (1982). Ribbon synapses in the developing intact and cultured organ of Corti in the mouse. J. Neurosci, 7, 942-957.

Sohmer, H., (1983). Neurologic Disorders. In E.J. Moore (Ed.), Bases of Auditory brain-stem evoked responses (Chapter 12). New York: Grune and Stratton.

Sohmer, H., & Feinmesser, M., (1967). Cochlear action potential recorded from the external ear in man. Annals of Otology, Rhinology and Laryngology, 76, 427-438.

Spoendlin, H.; (1979) Neural connections of the outer hair cell system. Acta. Otolaryngol. 87, 381-387.

Spoendlin, H., (1972). Innervation densities of the cochlea. Acta. Otolaryngol. 73, 235-248.

Spoendlin, H., (1969). Innervation patterns of the organ of Corti of the cat. Acta. Otolaryngol, 67, 239-254.

Spoor, A., (1965). Adaption of action potentials in the cochlea. International Audiology, 4(2), 154-160.

Spoor, A., & Eggermont, J.J., (1971). Action potentials in the cochlea. Masking, adaptation, and recruitment. Audiology, 10, 340-352.

Stevens,S.S., & Davis, H., (1938). Hearing: its psychology and physiology New York: John Wiley & Sons.

Stockard, J.E., Storkard, J.J., Westmoreland, B.F., & Corfits, J.L., (1979). Brainstem auditory evoked responses: Normal variation as a function of stimulus and subject characteristics. Archives of Neurology, 36, 823-831.

Stockard, J.J., Sharbrough, F.W., & Tinker, J.A., (1978). Effects of hypthermia on the human brain stem auditory response. Annals of Neurology, 3, 368-370.

Suzuki, T., Hirai, Y., & Horiuchi, K., (1977). Auditory brain stem responses to pure tone stimuli. Scand Audiol, 6, 51-56.

Suzuki, T., & Horiuchi, K., (1977). Effects of high filter on brain stem responses to tone pips. Scand. Audiology, 6, 123-126.

Teas, D.C., & Henry, G.B., (1969). Auditory nerve responses as a function of repetition-rate and background noise. Int. Audiol., 8, 151-163.

Teas, D.C., Eldridge, D.H., & Davis, H., (1962). Cochlear responses to acoustic transients and interpretation of the whole nerve action potentials. J. Acoust. Soc. Am., 34, 1438-1459.

Terkildsen, K., Osterhammel, P., & Huis in't Veld, F., (1975). Far-field electrocochleography. Adaptation. Scand Audiol, 4, 215-220.

Terkildsen, K., Osterhammel, P., & Huis in't Veld, F., (1973). Far field electrography electrode positions. Scand Audiol, 2, 141-148.

Thornton, A.R.D., & Coleman, M.J., (1975). The adaptation of cochlear and brainstem auditory evoked potentials in humans. Electroenceph and Clinical Neurophysiol, 39, 399-406.

Tsujimoto, A., Nakashima, T., Tanino, S., Dohi, T., & Kurogochi, Y., (1975). Tissue distribution of nicotine in dogs and rhesus monkeys. Toxicol. Appl. Pharmacol. 32, 21.

Tsuchitani, C., & Boudreau, J.C., (1964). Wave activity in the superior olivary complex of the cat. Journal Neurophysiology, 27, 814-827.

Venkatarao, K., Moore, E.J., & Lowrie, C., (1990). Characterization of an EPSP-like potential in the ventral-cord of Acheta domesticus. Presented at the American Speech-Language and Hearing Association National Convention held in Seatle, Washington.

Ward, W.D., (1973). Adaptation and Fatigue. In J. Jerger (Ed.), Modern developments in audiology (pp. 301-344) 2nd. ed. New York: Academic Press.

Ward, W.D., Glorig, A., & Sklar, D.L., (1959). Temporary threshold shift from octave-band noise: application to damage-risk criteria. J. Acoust. Soc. Am., 31, 522-528.

Warr, W.B., (1980). Efferent componentts of the auditory system. Ann. Otol. Rhinol. Laryngol. 89, Suppl. 74: 114-120.

Warr, W.B., & Guinan, J.J., (1979). Efferent innervation of the organ of Corti: two separate systems. Brain Res. 173, 152-155.

Weber, B.A., & Fujikawa, S.M., (1977). Brainstem evoked response (BER) at various stimulus presentation rates. J. Am Audiol Soc 3, 59.

Wegel, R.L., & Lane, C.E., (1924). The auditory masking of one tone by another and its probable relation to the dynamics of the inner ear. Physical Review, 23(ser 2), 266-285.

Weinberger, N.M., Kitzes, L.M., & Goodman, D.A., (1970). Some characteristics of the 'auditory neurophonic'. Experientia, 26, 46-48.

White, J.S., & Warr, W.B., (1983) The dual origins of the olivo-cochlear bundle in the albino rat. J. Comp. Neurol. 219, 203-214.

Xi, L., Dolan, D.F., & Nuttall, A.L., (1989). Characterization of the residual neural potential after application of tetrodotoxin to round window membrane. Assoc. Res. Otolaryngol. Abstracts XII St. Pietersburg, Florida.

Zollner, C., Karnahl, T., & Stange, G., (1976). Input-output function and adaptation behavior of the five early potentials registered with the earlobe-vertex pick-up. Archives of Otology, Rhinology, and Laryngology, 212, 23-33.

Zwislocki, J., (1978). Masking: Experimental and Theoretical Aspects of Simultaneous, Forward Backward and Central Masking. In E.C Carterette & M.P. Friedman (Eds.). Handbook of perception: Volume IV Hearing (pp. 283-336). New York: Academic Press.

Zwislocki, J., (1960). Theory of temporal auditory summation. J. Acoust. Soc. Am., 32, 1046-1060.

Zwislocki, J., Pirodda, E., & Rubin, H., (1959). On some post-stimulatory effects at the threshold of audibility. J. Acoust. Soc. Am., 31, 9-14.

Zwislocki, J., & Pirodda, H., (1952). On the adaptation, fatigue, & acoustic trauma of the ear. Experientia, 8, 279-284.