Spring 2009

Normative data for neurodiagnostic Auditory Brainstem Response testing (ABR)

David Alan Ness
Louisiana Tech University

NORMATIVE DATA FOR NEURODIAGNOSTIC AUDITORY BRAINSTEM RESPONSE TESTING (ABR)

by

David Alan Ness, B.A.

A Dissertation Presented in Partial Fulfillment
Of the Requirements for the Degree
Doctor of Audiology

COLLEGE OF LIBERAL ARTS
LOUISIANA TECH UNIVERSITY

May 2009

LOUISIANA TECH UNIVERSITY

THE GRADUATE SCHOOL

May 4, 2009

Date

We hereby recommend that the dissertation prepared under our supervision by David Alan Ness

entitled

Normative Data for Neurodiagnostic Auditory Brainstem Response Testing (ABR)

be accepted in partial fulfillment of the requirements for the Degree of Doctor of Audiology

Supervisor of Dissertation Research

Head of Department

Speech

Department

Recommendation concurred in:

Advisory Committee

Approved:

Director of Graduate Studies

Dean of the College

Approved:

Dean of the Graduate School

GS Form 13a
(6/07)

ABSTRACT

Auditory Brainstem Response (ABR) tests are procedures routinely performed to assess auditory function from the peripheral auditory system to the level of the lower brainstem. The ABR is used as a neurodiagnostic tool to detect retrocochlear pathologies of the auditory system, such as space occupying lesions, tumors, auditory neuropathy, and multiple sclerosis that effect the structures located above the level of the cochlea.

An ABR consists of eliciting and recording waveforms. These waveform recordings elicited are compared to normative data to determine normal versus abnormal (retrocochlear lesion) responses. Generalized normative data is available for ABR test results; however, research states it is important for each audiological clinical facility to develop its own set of standardized norms for each piece of testing equipment. Normative data has not been developed for the Nicolet Testing System, which is currently being used for ABR testing at Louisiana Tech University Speech and Hearing Center.

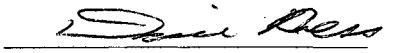
This study consisted of developing normative data for the Nicolet Testing System. In this study, ABR testing was performed on ten adult males and ten adult females. All participants were between the ages of 18-35 years. All participants also had normal outer and middle ear function and normal hearing sensitivity. Normative data was developed for the male group, the female group, and both groups combined. Means and standard

deviations were determined for waveforms I, III, and V and for the interpeak intervals of waveforms I-III, III-V, and I-V.

APPROVAL FOR SCHOLARLY DISSEMINATION

The author grants to the Prescott Memorial Library of Louisiana Tech University the right to reproduce, by appropriate methods, upon request, any or all portions of this Dissertation. It is understood that "proper request" consists of the agreement, on the part of the requesting party, that said reproduction is for his personal use and that subsequent reproduction will not occur without written approval of the author of this Dissertation. Further, any portions of the Dissertation used in books, papers, and other works must be appropriately referenced to this Dissertation.

Finally, the author of this Dissertation reserves the right to publish freely, in the literature, at any time, any or all portions of this Dissertation.

Author 

Date May 4, 2009

TABLE OF CONTENTS

ABSTRACT.....iii

LIST OF TABLES.....viii

LIST OF FIGURES.....ix

ACKNOWLEDGMENTS.....x

CHAPTER I: REVIEW OF LITERATURE.....1

Introduction.....1
Review of Literature.....4
Testing Parameters.....7
Latency.....7
Waveform Amplitude.....9
Factors Affecting ABR Results.....10
Participant Factors.....10
Age.....11
Gender.....12
Body Temperature.....12
Hearing Loss.....12
Medications.....14
Stimulus Factors.....14
Stimulus Type.....14
Stimulus Level.....15
Stimulus Rate.....16
Stimulus Phase.....18
Transducer.....20
Noise.....21
Recording Factors.....21
Filters.....21
Signal Averaging.....22
Artifact Rejection.....22
Presentations.....23
Electrodes.....24
Waveform Labeling.....24
Clinical Applications.....25
Vestibular Schwannoma.....26

Auditory Neuropathy....28
Sensitivity....29
Recommended Protocol for Neurodiagnostic Testing....29
Establishing Norms....30
Statement of the Problem....31

CHAPTER II: METHODS AND PROCEDURES....33

Participants....33
Experimental Procedure....33

CHAPTER III: RESULTS....38

Descriptive Statistics....38
Age....38
Male Results....38
Absolute Latencies....38
Interpeak Latencies....39
Female Results....40
Absolute Latencies....40
Interpeak Latencies....41
Combined Results....42
Absolute Latencies....42
Interpeak Latencies....43

CHAPTER IV: DISCUSSION....46

Purpose....46
Results....46
Published Normative Data....47

APPENDIX A: HUMAN SUBJECTS PERMISSION FORM....54

APPENDIX B: DEMOGRAPHICS FORM....56

REFERENCES....58

LIST OF TABLES

Table 1 Means and 95th Percentile Results for Absolute and Interpeak Latencies in the Male Group.....40

Table 2 Means and 95th Percentile Results for Absolute and Interpeak Latencies in the Female Group.....42

Table 3 Means and 95th Percentile Results for Absolute and Interpeak Latencies in the Combined Group.....45

Table 4 Musiek, Josey, and Glasscock's Normative Data.....48

Table 5 Antonellie, Bellotta, and Grandori's Normative Data.....49

Table 6 Schwartz, Pratt, and Schwartz's Normative Data.....50

Table 7 Joseph, West, Thorton, and Herman's Normative Data.....51

Table 8 Hall's Normative Data.....52

Table 9 Hood's Normative Data.....53

LIST OF FIGURES

Figure 1 Example of ABR Recording.....5

ACKNOWLEDGMENTS

I would like to acknowledge all individuals who provided me with guidance and support throughout the preparation of this dissertation. A special acknowledgment is given to the Director of my Dissertation Committee, Matthew Bryan; Au.D., CCC-A for his time and commitment to this dissertation. A special thanks is given to Sheryl Shoemaker, Au.D., CCC-A for her strength and guidance while completing this dissertation. Lastly, I would like to thank my classmates, friends, and family for their support throughout my academic career.

CHAPTER I

REVIEW OF LITERATURE

Introduction

Electroencephalogram (EEG) procedures are currently implemented in the medical field to assess and analyze cortical function of individuals with suspected dysfunctions and/or abnormalities of the central nervous system (CNS). Through the application of electrodes to the scalp, neuronal activity (i.e. electrical potentials or firing patterns) are recorded from both the cortex and the brainstem. The minute electrical potentials are amplified and displayed as a graph on a computer or oscilloscope and are used to evaluate cortical functioning.

Routinely used in the field of audiology, EEG procedures are used to evaluate the functioning of the auditory system. These procedures are called auditory evoked potentials (AEP); that is sound is being used as the stimulus and the electrical responses are generated from auditory sources within the brainstem and cortex. During AEP procedures, electrodes are placed on the mastoid process (or earlobes) and on the forehead. The auditory system is stimulated through as series of clicks or tone bursts and AEP responses are plotted as positive and negative fluctuations in microvoltage (mμ) as a function of time in milliseconds (ms). In recording of an AEP, the stimulus elicits a predictable electrical pattern in the form of positive and negative waveforms which occur consistently at specific points in time.

There are different AEP procedures performed to assess various portions of the auditory system. The three main categories of AEP testing implemented are early-latency responses, middle-latency responses, and late-latency responses. It is theorized that the early evoked responses are generated closer to the peripheral hearing mechanism while successive waveforms are believed to occur at the level of the lower and mid-brainstem as well as auditory cortex. Therefore, early latency responses typically occur within the first 10 ms while the later potentials (i.e., auditory cortex) occur as late as 1000 ms. The stimulus and electrode montage differs based on the auditory area being measured.

Early-latency responses occur within 0.2-10 ms after the stimulus is presented to the participant. The most routinely performed early-latency response procedures are the electrocochleography (ECochG) and the Auditory Brainstem Response (ABR) evaluation. These procedures assess areas of the middle ear, inner ear, and lower auditory brainstem function. According to Hall (2006), early-latency responses have the smallest magnitude of all the AEP procedures since they assess functioning of regions most distal to the cortex. These anatomical structures generating the electrical potential consist of few neurons resulting in a much smaller microvoltage change when stimulated.

Middle-latency responses occur within 10-50 ms after the stimulus is presented to the participant. Burkard, Don, and Eggermont (2007) found that middle-latency responses are useful for assessing regions of the higher brainstem and auditory cortex, including the thalamus and medial geniculate body. The main disadvantage of middle-latency response testing is responses are skewed if the participant is in a sleeping or in a sedated state. This makes testing difficult on infants and/or developmentally delayed individuals.

Late-latency responses, also known as cortical auditory evoked potentials, occur within 50-1000 ms after the stimulus is presented to the participant. Hall (2006) found that late-latency responses can be implemented to estimate hearing threshold levels, as well as an individual's ability to process speech. There are several late-latency responses performed, the most routinely performed procedures are the P1-N1-P2 Complex, Mismatch negativity, P300, and N400. In general, the later these responses occur, the larger the amplitude of the response.

While later evoked potentials are useful in assessing higher cortical functioning, the ABR is the most useful and routinely performed AEP procedures. Therefore, the remainder of this discussion will pertain exclusively to the characteristics, parameters, and influencing factors pertaining to the ABR.

Review of Literature

The ABR is an objective, early-latency response implemented to assess auditory function from the peripheral auditory system to the level of the lower brainstem. Ballachanda, Moushegian, and Stillman (1992) defined an ABR as "a series of scalp-recorded electrical potentials of neural activity generated within the auditory nerve and nuclei and tracts of the lower brainstem during the first 10 msec [milliseconds] after a click stimulus" (p. 275).

The ABR typically serves two purposes in clinical audiology. First, the ABR is used as a neurodiagnostic tool to detect retrocochlear pathologies of the auditory system, such as space occupying lesions, tumors, auditory neuropathy, and multiple sclerosis that effect the anatomical structures located above the level of the cochlea. Additionally, ABR evaluations are routinely implemented to determine auditory sensitivity. Burkard et al. (2007) found that the ABR is a useful test for estimating hearing levels in individuals who cannot complete a traditional, behavioral audiological evaluation (e.g., infants, small children, and developmentally delayed). The focus and purpose of this study is limited to the examination of the neurodiagnostic ABR. When ABR appears in the remaining portion of this paper the author is referring to a neurodiagnostic ABR.

According to Burkard et al. (2007), an ABR consists of seven recognizable waveforms, which are labeled with roman numerals I-VII. Clinically, only waveforms I-V are identified and analyzed. Waveforms II and IV are often variable; therefore, for clinical purposes, an ABR is analyzed in terms of waveforms I, III, and V. The waveform recordings elicited during an ABR are used to determine normal versus abnormal (retrocochlear lesion) responses. Figure 1 provides an example of an ABR recording.

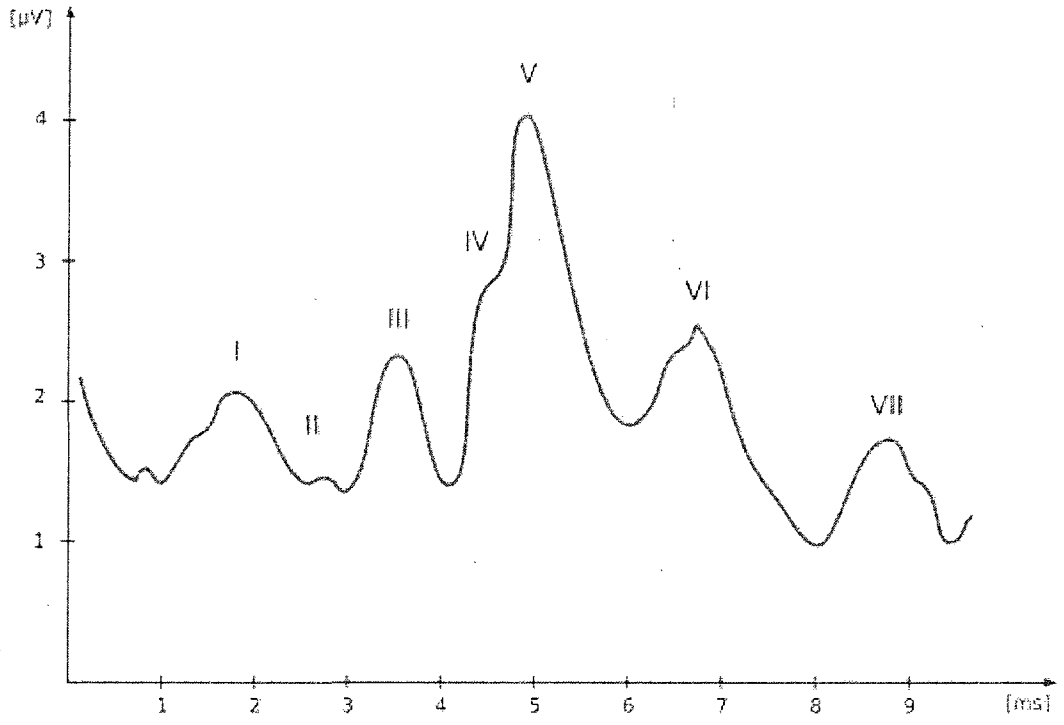


Figure 1 Example of ABR Recording.

Song, Banai, Russo, and Kraus (2006) stated the ABR "is generated by synchronous firing of structures along the ascending auditory pathway, which include the auditory nerve, cochlear nuclei, superior olivary nuclei, lateral lemnisci, and inferior colliculi" (p. 233). The exact anatomical structures generating the peaks of the ABR responses are still debated; however, many researchers have agreed upon proposed possible loci (ASHA Working Group, 2008; Bhattacharyya & Scott, 2006; Hall, 2006; Hood, 1998b). Waveform I arises from the distal portion of the eighth nerve (where the fiber tracts leave the cochlea), while waveform II arises from the proximal portion of the eighth nerve (where the fiber tracts enter the lower brainstem). The exact location or structures that generate waveforms III-V is not as conclusive as waveforms I and II, and several structures may be involved. Waveform III is believed to arise from the cochlear

nucleus and pons regions on the ipsilateral side (same side the stimulus is presented) of stimulation. Waveform IV is thought to arise from the superior olivary complex and surrounding fiber tracts on both the ipsilateral and contralateral side (opposite side the stimulus is presented) of stimulation. Waveform V is believed to be generated from neurons in the lateral lemniscus, inferior colliculus, and the fiber tracts connecting them on the contralateral side of stimulation.

Hood (1998b) also agreed that the exact neural generators of the later waveforms are not conclusive. She stated

> Recordings from the cochlear nucleus correspond with the surface-recorded Wave III, suggesting that Wave III is generated mainly by neurons in the cochlear nucleus. The neural generators of Wave IV are uncertain, although third-order neurons in the superior olivary complex are most likely involved; other contributors may include the cochlear nucleus and the nucleus of the lateral lemniscus. Wave V may be related to activity in the lateral lemniscus and inferior colliculus, but it should be emphasized that peaks IV, V, VI, and VII of the ABR are complex, with more that one anatomical structure contributing to each peak and each structure contributing to more than one peak. (p. 15)

In summary, research is conclusive that the eighth cranial nerve is the neural generator of waveforms I and II of the ABR, with the distal portion contributing more to waveform I and the proximal portion contributing more to waveform II. The exact neural generators of waveforms III-V is inconclusive and it is believed that several structures in the brainstem contribute to each of these waveforms. Researchers such as Hall (2006) have agreed that the fiber tracts surrounding the cochlear nucleus significantly contribute

to waveform III, while the superior olivary complex and its surrounding structures are the primary generators of waveform IV. Researchers have also agreed that there may be several structures contributing to waveform V with the lateral lemniscus and inferior colliculus regions being the primary generators.

Testing Parameters

Certain parameters are used to evaluate ABR waveforms to determine if the evoked responses are within normal limits. The two main parameters analyzed are latency and amplitude. In neurodiagnostic testing, waveform latency is predominately used to determine "normal" versus "abnormal" results. The rationale for its widespread use is due to the reliability and consistency of responses. Amplitude, which contributing to neurodiagnostic testing, is highly variable from participant to participant.

Latency

Latency is the time taken for the responses to occur following a stimulus presentation, and is measured in ms. Waveform responses are labeled by looking for positive microvoltage peaks at specific points in time. Burkard et al. (2007) found that peak latencies are determined by how the stimulus travels through the structures of the ear and the brainstem. If there is a clear pathway from the outer ear through the brainstem, latency values should occur within a designated time period. If any of the above structures are disordered, a prolongation of latency waveform can occur and occasionally waveforms can disappear all together.

Latency values are analyzed by calculating the absolute latency values, interpeak latency values, and interaural latency difference. The absolute latency is the time taken for each waveform to occur after a stimulus is presented to the ear. Hall (2006) found that

when using click stimuli at high intensity levels (70-90 dBnHL), waveform I occurs at approximately 1.5 ms after the stimulus is presented to the ear. The following waveforms (i.e., II, III, IV, and V) occur at approximately 1.0 ms intervals of waveform I, so 2.5 ms for wave II, 3.5 ms for wave III, 4.5 ms for wave IV, and 5.5 ms for wave V.

The absolute latency is also affected by how the signal travels from the basal portion to the apical portion of the cochlea. Signals traveling through the apical portion of the cochlea result in increased latency compared to those traveling through the basilar portion. Low frequency sounds travel through the apical portion of the cochlea, while high frequency sounds travel through the basilar end; resulting in increased latency for low frequency stimuli compared to higher frequency stimuli.

The interpeak latency (IPL) value is the time difference in absolute latency between waveforms. The I-III, III-V, and I-V IPLs are calculated when all waveforms are labeled in terms of absolute latency. These IPLs are then compared to normative values to determine if they occur within normal limits. The IPL should be approximately 2.0 ms for waveforms I-III, 2.0 ms for waveforms III-V, and 4.0 ms for waveforms I-V. According to Hood (1998b), the IPL should not be more than ±0.4 ms from the norm to be considered normal.

The waves I-III interval represents synchronous activity in the eighth nerve and lower brainstem, whereas the III-V interval may reflect activity primarily within the brainstem. The I-V interval is considered a representation of overall activity from the eighth nerve and the nuclei and tracts of the brainstem responsive to auditory stimuli. (Hood, 1998b, p. 17)

The interaural latency difference (ILD) is the absolute latency difference of waveform V between the ipsilateral recordings for each ear. For example, if the absolute latency of wave V is 5.5 ms for the right ear and the absolute latency of wave V for the left ear is 5.7 ms, the ILD is 0.2 ms. According to Hood (1998b) the interaural latency difference is a useful tool for diagnosing retrocochlear lesions of the auditory system. The ILD should not differ by more than 0.4 ms if the participant has similar hearing between ears; however, caution must be taken when an asymmetrical hearing loss is present.

Waveform Amplitude

The amplitude is the magnitude or power of the response and is measured in microvolts (μV). Due to the variability among participants, less emphasis is placed on the amplitude values of the waveforms compared to the latency values. Burkard et al. (2007) stated "the amplitudes of ABR peaks reflect the number of neural elements that are activated synchronously. Thus, both the number of elements and the degree of synchrony affect the amplitudes" (p. 233). Burkard and fellow researchers (2007) found that the absolute amplitude values are variable among participants even when the noise in the testing environment is controlled. Additionally, Katz (2002) noted that elderly individuals showed a decrease in waveform amplitude when compared to young and middle-aged adults.

While amplitude is used to a lesser extent than latency when evaluating neurodiagnostic ABRs, there are always exceptions. The only amplitude measurement in neurodiagnostic ABR testing is the V/I amplitude ratio. The V/I amplitude ratio is the difference in amplitude between waveforms V and I for each ear. According to Hall (2006), the V/I amplitude ratio is calculated by determining the absolute peak amplitude

point on each waveform from a baseline or reference point and comparing the two. The amplitude of waveform V should always be greater than waveform I by a ratio of at least 1μV. If the ratio falls below 0.5μV, this is an indication of a possible retrocochlear lesion.

Factors Affecting ABR Results

There are a variety of factors that can affect and distort ABR waveforms, including participant factors, stimulus factors, recording factors, and waveform labeling. Testing results are also affected by the type of electrodes used and where they are placed on the participant. All of these factors must be controlled to ensure valid and reliable electrophysiological responses are obtained.

Participant Factors

For accurate and valid ABR results, the participant must be in a relaxed state for optimal testing to be completed. This is important because any type of participant movement may skew the test results for that particular trial or run. Patient movement results in muscle contraction, which generates an electrical (neural) signal. When this occurs it is likely that the scalp electrodes can detect this neural activity and therefore the auditory response may be obscured in "noise". This type of noise is called myogenic noise and must be controlled when conducting testing. Typically this can be achieved by inviting the participant to relax and even sleep if possible. It must be clearly conveyed to the participant what the test involves and what is expected of them during testing. Participant factors can also be controlled by conducting testing in a quiet, dark, comfortable environment where the participant can relax free of outside noises or distractions.

There are some participant factors that cannot be controlled or altered, and therefore must be accounted for when conducting testing. This includes the patient's age, gender, body temperature, and hearing loss. In addition, certain medications can also affect latency and amplitude values; therefore must be avoided prior to testing.

Age.

Infants and elderly individuals show increased latency values compared to young and middle-aged adults. According to Hood (1998b), infant ABR recordings show increased latency values until the child reaches approximately 12-18 months of age. The delays in latencies reflect the maturational development of the central auditory nervous system of infants from birth through 18 months of age. Hood (1998b) found that waveform I of infants often show slight delays, while waveform V typically shows the longest delay compared to adult recordings. The increase in wave V latency of infants results in an increased I-V interpeak interval latency value (approximately 5.0 ms) when compared to the I-V interpeak latencies in adults. She stated that "this prolongation may be related to cochlear maturation, neuronal maturation, reduced efficiency in external and/or middle ear sound transmission, and occasionally collapsing ear canals" (p. 61).

Advances in age have also shown effects on latency and amplitude values of ABR recordings. According to Hall (2006), individuals above 60 years of age show increased latency values for the later waveforms (waves III-VII) and decreased amplitude for all waveforms compared to middle-aged adults. This increase in latency of waveforms III-VII results in increased interpeak latency values for older adults. There is speculation regarding the differences in ABR results for middle aged adults compared to the older adult population. It has been proposed that these differences are due to deterioration of

the auditory brainstem structures of older adults, resulting in effects to the later waveforms.

Gender.

ABR recordings are also different for males compared to females. According to Burkard et al. (2007), females show shorter absolute latency values, smaller interpeak interval values, and increased waveform amplitude compared to males. These differences between sexes have been attributed to the average head size differences between males and females. On average, males have larger head sizes, larger cochleas, and longer fiber tracts connecting the cochlea to the central auditory cortex than females do. These factors cause the electrical potentials generated by the auditory system to travel further to the recording electrodes located on the scalp. This increased distance results in increased latency values and decreased amplitude values for males when compared to females.

Body Temperature.

Differences in participant body temperature can also skew results. Katz (2002) found that a decrease in participant body temperature leads to a decrease in waveform amplitude and an increase in waveform latency. Decreased body temperature can be the result of drug and alcohol use or hypothermia.

Hearing Loss.

Hearing loss is another factor that must be accounted for that can affect ABR results. The effect the hearing loss has on test results depends on the type, severity, and configuration of the loss. Sininger (1992) proposed that "a hearing loss can degrade waveform morphology for the earlier waveforms, increase latency, and decrease amplitude. If a hearing loss is present, correction factors must be used" (p. 16). Hood

(1998b) found that for individuals with auditory thresholds at or above 50 dB HL from 2000-4000 Hertz (Hz), waveform latency values and waveform morphology may be affected. The affects of the hearing loss may result in an absent or delayed waveform I, delayed waveform V, and/or poor overall waveform morphology. The more severe the hearing loss in the 2000-4000 Hz range, the greater the chance it affects ABR results. Hall (2006) found that when testing at high intensity levels (>80 dBnHL), a hearing loss does not effect ABR results until auditory thresholds reach at least 50-60 dBHL from 1000-40000 Hz.

The interpeak interval values may also be affected by sensorineural hearing loss. According to Hood (1998b), individuals with very steep high frequency hearing losses (i.e., normal hearing in the low frequencies with a steep decrease in hearing sensitivity in the mid to high frequencies) have shown delayed latency values for waveform I and minimal delays or normal latency values of waveform V. This delay of waveform I results in a reduced I-V IPI value which may be falsely identified as falling below the normal range. Hall (2006) found that ABR interpeak waveforms are less affected by a flat hearing loss compared to a steep sloping high frequency hearing loss, which he attributed to basilar membrane functioning. That is, a flat hearing loss impacts all portions of the basilar membrane, while a high frequency hearing loss only affects the basal portion of the basilar membrane.

Conductive hearing loss can also impact ABR waveforms. According to Hall (2006), if a conductive hearing loss is present, all ABR waveforms show increased latency values. Absolute latencies shift in time due to the presence of the conductive pathology. Since all waveforms show increased latencies, the interpeak waveform

latencies should not be affected. Normal interpeak waveform values help differentiate a conductive hearing loss from a retrocochlear pathology.

Medications.

Certain medications have been shown to affect latency values of ABR recordings. Hood (1998b) stated

> Abnormal ABR's have been reported in conjunction with medications such as phenytoin, lidocaine, and diazepam. Also, carbamazepine (CBZ) monotherapy in epileptic patients has been reported to result in prolongation of the peak latencies of Waves I, III, and V and prolongation of Waves I-III and I-V intervals. Documentation of medications should assist in appropriate interpretation of test results. (p. 62)

Stimulus Factors

The type of stimulus (e.g., tone pips, clicks) being presented to the participant determines the specific response that is elicited and assesses different areas of the auditory system. There are several stimulus factors that need to be considered prior to testing, including the stimulus type, rate, phase, and presentation level used. There are also different types of transducers that can be used during testing, which affects the stimulus.

Stimulus Type.

The two most common types of stimuli used in ABR testing are clicks and tone bursts; however, clicks are the stimulus of choice for neurodiagnostic ABR testing. According to Hall (2006), the use of click stimuli primarily tests the 1000-4000 Hz

region of the cochlea and auditory system, which does not account for the low frequency regions. The ASHA Working Group (2008) stated

> Clicks are the most commonly used stimuli for eliciting the ABR. The abrupt onset and broad spectrum of a click result in synchronous excitation of a broad population of neurons. The click is usually the most effective stimulus and can provide high frequency information. (p. 15)

In other words, the abrupt click stimulus promotes the greatest amount of neural activity within the lower brainstem. This increase in neural activity provides the most robust waveforms with the best morphology. This is the reason why neurodiagnostic ABR evaluations are typically conducted using a click stimulus. For neurodiagnostic testing, the stimulus should be presented at high intensity levels so all waveforms can be identified.

Stimulus Level.

The stimulus level is the intensity of the stimulus presented to the participant. As a general rule, when the intensity of the stimulus is increased above a person's auditory threshold, the amplitude of the ABR waveforms increases and the latency decreases. For neurodiagnostic testing it is optimal to perform testing at high intensity levels (e.g., 70-100 dBnHL). At this high intensity level, neural synchrony of the VIII nerve and lower brainstem is optimized and results in robust responses. The increased amplitude results in better morphology and therefore, makes the identification of absolute and interpeak latencies much easier to identify. Hall (2006) found that waveforms I-V are most easily recognizable and distinguishable at levels well above auditory thresholds.

Stimulus Rate.

The stimulus rate refers to the number of times the stimulus is presented to the participant per second. As the stimulus rate is increased, waveform amplitude values are reduced and latency values are increased; as the rate is decreased, amplitude values increase and the latency values decrease. Burkard et al. (2007) suggested that increasing the stimulus rate increases the latency of waveform V; however, it has shown little effect on waveform I, causing the interpeak interval to increase with the use of high stimulus rates.

According to Sininger and Don (1989), implementing high click rates during ABR testing reduces the amount of time taken for testing to be completed. They also found that increases in the click rate above 30 clicks per second results in neural adaptation of the auditory system, which may lead to reduced waveform amplitude and morphology. Implementing a high click rate makes it more difficult to accurately identify waveforms. The ASHA working group (2008) found that "faster rates prolong the latencies of all the waves progressively, so that Wave I is delayed approximately 0.1 ms and Wave V is delayed approximately 0.3 ms between rates of 10 and 50/second. High rates also decrease the amplitudes of waves prior to Wave V" (p. 17).

Hall (2006) found that implementing faster presentation rates results in reduced testing time, while slower rates result in more robust responses. He recommends using an odd number to reduce the chances of electrical interference. Research has shown that rates above 20 clicks/second have shown increases in waveform latency and decreases in amplitude. The stimulus rate most effective differs for neurodiagnostic testing compared to threshold testing.

According to the ASHA Working Group (2008)

> Low rates are advisable when a full complement of waves is necessary, such as in the case of otoneurologic evaluations. For other purposes, such as threshold testing, rates of 25-40/second are acceptable because the amplitude of Wave V is minimally reduced. This improves the efficiency of ABR measurements because more averages can be taken in the same period of time. (p. 17)

According to Hall (2006), testing with high stimulus rates after waveforms have been properly identified using low rates, is a useful diagnostic tool for identifying abnormalities to the CNS. Presenting stimuli at fast rates stresses the auditory system and can result in abnormally prolonged or absent waveforms if certain abnormities exist. This evaluation is often called a rate study and is used as an additional tool to evaluate the lower auditory brainstem for retrocochlear disorders. Prior to performing a rate study, all waveforms must be clearly defined and distinguishable. When performing a rate study, only wave V is trying to be identified. Hall (2006) stated

> Abnormal latency shifts or disappearance of later waves at very rapid stimulus rates have been reported in various types of peripheral and CNS pathology, including eighth-nerve tumors, epidermoid tumor of the fourth ventricle, head injury, hypoxia, mixed CNS diseases, and multiple sclerosi. (p. 184)

Therefore, a rate study is often conducted after an ABR is collected at a lower stimulus rate and the absolute and interpeak latencies are evaluated against normative values. According to Hall (2006), as a general rule, the latency of wave V should increase by 0.1 ms for every increase of 10 clicks per second of the stimulus. As an example, wave V collected at a slow rate of 19.1 clicks per second yielded a wave V absolute

latency of 5.5 ms. If the rate is then increased from 19.1 to 89.1 clicks per second, wave V should increase to a latency of no longer than 6.2 ms. A rate study wave V shift of more than this (0.7 ms) would be considered abnormal and a positive finding for a retrocochlear pathology.

Stimulus Phase.

The stimulus phase or polarity refers to the initial deflection of the transducer when the stimulus is presented. There are three stimulus polarities used to perform ABR testing: rarefaction, condensation, and alternating. The stimulus is in the negative phase when using a rarefaction polarity, the stimulus is in the positive phase when using a condensation polarity, and the stimulus alternates between rarefaction and condensation when using an alternating phase.

The stimulus phase affects the morphology, amplitude, and latency of the waveforms. According to Fowler (1992), when using intensity levels well above hearing thresholds, rarefaction stimuli have been shown to increase neural activity; while near thresholds, the effects of the stimulus phase are minimal. At high-intensity levels, waveforms I, III, and V occur at shorter latency values for rarefaction stimuli then they do for condensation stimuli. The interpeak interval remains constant regardless the stimulus phase used, since the latency between waveforms remains unchanged.

Hood (1998b) found that a rarefaction stimulus produces an outward movement of the transducer, which leads to an initial outward movement to the structures of the middle ear and an upward movement to the basilar membrane in the inner ear, resulting in hair cell depolarization. A condensation stimulus produces an inward movement of the transducer prior to an outward movement, which results in increased time taken for hair

cell depolarization to occur. Therefore, the early components of the ABR (waveforms I and II) result in reduced latency and increased amplitude values when implementing a rarefaction stimulus. This means that using a rarefaction stimulus provides the greatest chance for accurately identifying and labeling waveform I. According to Hall (2006), when using click stimuli, a rarefaction phase results in a reduced latency and increased amplitude for waveform I. The reduced latency is consistent with the cochlear mechanics that take place when implementing a rarefaction click compared to a condensation click. Hall (2006) stated, "Perhaps the most consistent polarity-related ABR finding is shorter latency for wave I (on the average about 0.07 ms) for rarefaction clicks" (p. 185).

Research regarding the effects of the stimulus phase is not as conclusive for the later waveforms (wave III-V) as it is for the early waveforms. Hood (1998b) found that the amplitude of waveform V is greater when using a condensation stimulus compared to a rarefaction stimulus. She reports no differences in wave V latency regardless of the polarity implemented. Hall (2006) noted that previous research conducted to determine the effects of stimulus polarity of waveforms III and V is inconsistent. These inconsistencies may be due to experimental differences in research methodology regarding the participants tested and the stimulus rates and levels implemented during testing. Hall (2006) stated that "there is no consensus on which of the ABR wave components are most affected or most consistently affected. That is, selected waves, such as waves I and V, may have shorter latencies for rarefaction clicks, whereas another wave, such as wave III, may have shorter latency for condensation clicks" (p. 185).

According to Hood (1998b), the use of an alternating polarity can be implemented to reduce stimulus artifact. It is designed to reduce artifact by canceling responses that are

out of phase; however, when used during air conduction testing, this alters the ABR response. Hood (1998b) stated that "the introduction of insert earphones with an inherent delay line of 0.9 ms has served to reduce the interference of stimulus artifact with the response. Therefore, the only time that alternating-polarity stimuli are recommended is when using a bone-conduction transducer" (p. 53).

Transducers.

A transducer is a device used to transfer energy from one form to another. There are several different transducers that can be used for ABR testing, including supra-aural ear phones, insert earphones, and bone conduction transducers. The type of transducer used determines or shapes the stimulus, referred to as the stimulus spectrum or to the frequency response of the stimulus as it goes through the transducer to the ear. It is ideal for the stimulus spectrum to have a flat frequency response (i.e., intensity levels are equal across all frequencies). If frequency alterations occur in the spectrum, those frequency regions with increased amplitude may provide more stimulation than intended and those regions with decreased amplitude may not provide enough stimulation. Thus, the stimulus being presented to the participant may differ from the intended stimulus.

According to Laws, Roller, and Perry (1993), supra-aural earphones were the most common transducer used in ABR testing until the development of insert earphones. They found that the use of insert earphones decreases the need for contralateral masking because inserts increase the interaural attenuation by approximately 10-12 dB over supra-aural headphones during ABR testing. Laws and fellow researchers (1993) stated that insert earphones provide certain advantages, "such as ambient noise exclusion, less likelihood of recording electrical artifact, and increased interaural attenuation" (p. 60).

Another advantage of using insert earphones is the prevention of collapsing ear canals. The use of supra-aural headphones can push down on the tragus portion of the outer ear creating a closed or collapsed ear canal, resulting in an artificial conductive hearing loss and invalid ABR responses. The possibility of a collapsing ear canal is eliminated when using insert earphones, since there is no pressure being forced on the tragus.

Noise

In auditory evoked potential testing, noise refers to any electrical potential that is not part of the auditory response to stimulus. In other words, any electrical potential that is measured by the electrodes that is not part of the auditory response is considered noise. Noise can be the result of electrical interference from computers and lights, or muscle artifact or movement from the participant themselves. The goal of the test administrator is to reduce the noise present improving the signal-to-noise ratio (SNR). The higher the SNR, the more likely the elicited responses are true auditory evoked potentials and not responses from noise sources.

Recording Factors

Recording factors are techniques employed to prevent unwanted noise from skewing true electrophysiological responses. They are used to help determine what responses are the results of noise and what responses are truly evoked. The recording factors used include filter settings, signal averaging, artifact rejection, and the number of presentations performed.

Filters.

The use of filtering is an effective technique to improve the SNR. Filters are designed to allow electrical signals with certain frequency parameters to pass through unaffected while rejecting all other signals. ABR testing typically involves the use of a

band-pass filter, which consists of a low-pass filter and a high-pass filter. The filter settings should be set to reduce the effects of low and high frequency noise while allowing the response to pass through. Burkard et al. (2007) found that "for the click-evoked ABR, the high-pass cutoff most often used is 100 Hz, and the most common low-pass cutoff is 3000 Hz" (p. 231).

Signal Averaging.

Signal averaging is a technique used to differentiate true electrophysiological responses from noise. This is automatically employed through the amplifier of most ABR testing software. Signal averaging consists of sampling the voltage of the response from many different points to determine if the response is the result of noise or if it is a true elicited response. Each time the stimulus is presented, the response is analyzed at each point and an average voltage level is determined for each point. Hall (2006) proposed that responses that are the result of noise appear randomly, while electrophysiological responses occur consistently. The concept behind signal averaging is that if noise is measured during the ABR recording it is random in nature. If sufficient recordings are made and averaged together the random noise is canceled from the electrophysiological response. This process reduces the random noise while enhancing the consistent auditory response, thus increasing the SNR or the ABR. According to Hall (2006), "conventional (mean) averaging is invariably utilized clinical to extract and enhance auditory evoked responses embedded within background neurogenic and neurologic activity" (p. 207).

Artifact Rejection.

Artifact rejection is another clinically useful technique that is also automatically performed by the ABR amplifier to prevent unwanted responses from skewing test

results. According to Hall (2006), artifact rejection consists of sampling the voltage of each response. If the voltage of the response exceeds a certain sensitivity limit set on the amplifier, the response is rejected and is not sent to the signal averaging device. The primary purpose of artifact rejection is to prevent these responses from being averaged into the response. Responses with extremely large voltages are not auditory responses and often occur due to muscle activity as a result of movement during testing. If these large, non-auditory responses are sent to the signal average process, the ABR morphology suffers and the SNR decreases (Sanchez & Gans, 2006). In other words, artifact rejection "...evaluates the amplitude of the incoming noise from the electrodes for individual sweeps. If the noise exceeds a predetermined microvolt level, the sweep is rejected from the computer memory and not included in the averaging process" (Sanchez & Gans, 2009, 154-155).

Presentations.

The number of presentations or sweeps performed refers to how many stimulus presentations are performed for each obtained response. The number of sweeps performed is determined by the test administrator prior to testing and can range from 100 to 2500 sweeps. The number needed to ensure true elicited responses is variable among participants and presentations. According to Hall (2006), "the number of sweeps required in ABR measurement is highly dependent on the signal-to-noise ratio, on both the magnitude of ABR components and the amount of measurement noise arising from diverse sources" (p. 211). In clinical evaluations, when all waveforms can be accurately identified, the presentations/averaging can be stopped.

Electrodes.

The type of electrodes used and the manner in which they are placed affects the recordings of the elicited response. The most common electrode array involves an inverting and non-inverting electrode montage. This array consists of inverting electrodes on the right (A2) and left mastoids or earlobes (A1), a non-inverting electrode on the high forehead (Fz), and a ground electrode on the lower forehead (FPz). Hall (2006) stated the following objectives of electrode placement:

> (1) consistent placement among subjects, (2) anatomically accurate placement, (3) low inter-electrode impedance (less than 5000 ohms), (4) balanced inter-electrode impedance (difference between electrodes less than 2000 ohms), (5) secure and consistent attachment throughout the test session, and (6) minimal discomfort and no risk to the subject. (p. 80)

Waveform Labeling.

The absolute latencies and the IPL values are determined by where the waveforms are labeled on the response. This is a subjective measurement made by the test analyzer that determines normal versus abnormal responses, so the analyzer must be accurate and consistent. Where the waveforms are labeled depends on the overall morphology, or appearance of the responses. If the morphology is poor, the waveforms may be difficult to label even if the latency and amplitude appear normal.

There are two classification systems routinely administered to determine the precise latency values of the waveforms, the peak method and the shoulder method. When using the peak method, the waveform is labeled where the highest voltage point (peak) occurs on the selected waveform. When using the shoulder method, the final point

on the waveform before the response amplitude begins to decrease is labeled as the precise latency. Amplitude values are determined by calculating the voltage difference between the peak of the waveform and the following trough, or by calculating the voltage of the peak with a baseline point (Hall, 1992).

The shoulder method is used when multiple waveforms are fused together. This occurs most often with waveforms IV and V which can be fused together resulting in what is called a wave IV/V complex. The wave IV/V complex looks like one large waveform. If the peak method is used in this situation, the examiner may actually be mislabeling the exact location of wave V, resulting in abnormal results. Therefore, the shoulder method is often used to overcome the wave IV/V complex.

Hood (1998b) found that waveform I can difficult to identify in many participants, especially if high frequency hearing loss is present. Waveform I may be absent or reduced even if waveforms III and V are present at robust amplitudes and normal latency values. The inability to identify waveform I results in the inability to determine the I-III and I-V interpeak interval values (IPI). The IPI values are important in diagnosing cochlear versus retrocochlear site of lesion, therefore it is important to correctly identify wave I. If waveform I is reduced or absent certain measures can be taken to increase the waveforms amplitude and morphology. For instance, Hood (1998b) recommended increasing stimulus intensity, using rarefaction clicks, and decreasing click presentation rate.

Clinical Applications

The development of ABR testing has allowed for a routine method of differentiating between cochlear and retrocochlear disorders of the auditory system.

Neurodiagnostic ABRs are designed specifically to diagnose dysfunction and/or lesions of the eighth cranial nerve and/or areas of the lower brainstem. This includes space occupying lesions, such as neoplasms of the cerebellopontine angle (CPA), vestibular schwannomas, neurofibromas, and meningiomas. The use of ABR testing has also been implemented to identify and diagnose auditory neuropathy/dys-synchrony.

If retrocochlear pathology exists, certain symptoms are often present. According to Hall (2006), common symptoms that determine if an individual should be referred for an ABR include an asymmetrical or unilateral sensorineural hearing loss, poor word recognition scores (<30%) compared to pure tone auditory thresholds, episodes of vertigo, aural fullness, and/or unilateral tinnitus. Bhattacharyya and Scott (2006) suggested that if an ABR yields abnormal results, a magnetic resonance imaging (MRI) evaluation should be administered. The average cost of an MRI is five times the cost of an ABR, so the use of an ABR as an initial diagnostic tool is a cost efficient measure.

Vestibular Schwannoma

According to Hall (2006) vestibular schwannomas are benign tumors that arise from the Schwann cells that cover the eighth cranial nerve. These are usually unilateral and are most frequent among middle-aged adults. The incidence of a vestibular schwannoma is around 9:100,000 and are twice as prevalent among females. Hall (2006) suggested

> The vestibular schwannoma typically grows to displace, deform, and/or stretch the normal auditory nerve fibers, which may eventually be compressed into a thin ribbon. In addition to compressive effects of the eighth-nerve tumor, symptoms

> may be due to compromise of the blood supply to the nerve or inner ear or to interruption of cochlear fluid flow. (p. 372)

Neurofibromas are genetic disorders which also arise from the schwann cells. These are most often effect the eighth cranial nerve. There are two different forms of neurofibromas, neurofibromatosis 1 (NF 1) and neurofibromas 2 (NF 2). Hall (2006) found that NF 1 is much more prevalent than NF 2 and typically appears earlier in life than NF 2. NF 1 is a peripheral abnormality and is usually bilateral, while NF 2 is a central abnormality, meaning it occurs higher in the brainstem. The most common symptoms of neurofibromas are hearing loss and café au lait spots (skin abnormalities).

Hall (2006) classified meningiomas as tumors arising from meningothelial arachnoid cells. Meningiomas are also more prevalent among females than males. The symptoms present depend on the location and size of the lesion. Meningiomas typically appear later in adulthood and may have no effect on auditory functioning.

Hood (1998b) proposed that the presence of a retrocochlear disorder, such as an acoustic neuroma, can affect the ABR waveforms in several different ways. It may result in prolongation of the absolute latencies of the waveforms, prolongation of the interpeak interval latency values, absent waveforms, or degraded morphology of the waveforms. The result the lesion has on the ABR depends on the size of the lesion and where it occurs in the auditory system. The most prevalent patterns for identifying cerebellopontine angle tumors are absent waveforms III and V, or a delayed wave I-V interpeak interval latency value. Abnormal wave V/I amplitude ratios have also been identified in individuals with confirmed tumors. Hood (1998b) found that in a study of 61 patients with eighth nerve or brainstem tumors, 30% of the patients had no recognizable

waveforms, 44% showed some absent waveforms, and 26% of the patients showed abnormal waveform latency values.

Auditory Neuropathy

According to Hood (1998a), auditory neuropathy is a condition that affects individuals of all ages. These individuals show normal outer hair cell functioning but abnormal neural transmission of sound from the inner ear system through the auditory brainstem. Individuals with auditory neuropathy may have normal sound awareness abilities, but difficulties discriminating speech.

Hood (1998a) found that audiological testing typically results in normal otoacoustic emissions and absent ABR responses. Behavioral testing has shown mixed results, with pure tone results ranging from normal hearing to a profound sensorineural hearing loss. Speech testing is also variable, but is usually very poor especially in noisy environments.

The exact site of lesion causing the auditory neuropathy has not been clearly identified. Hood (1998a) proposed that there are several possible sites of lesion, including the inner hair cells and/or the synapses occurring within the inner hair cells, the VIII nerve fibers, or the tectorial membrane. An auditory neuropathy may also affect the afferent and/or the efferent pathways.

According to Hood (1998a), the ABR is one of the most useful tools for diagnosing auditory neuropathy. If a neuropathy exists, the ABR waveforms are absent or severely abnormal; however, a clear cochlear microphonic is present with a reversal of stimulus polarity at high levels. Diagnosing auditory neuropathy as soon as possible can lead to appropriate intervention.

Sensitivity

The sensitivity of an ABR refers to its ability to detect abnormalities of the auditory system. For space occupying lesions, the size of the lesion is proportionate to the sensitivity of the ABR. For larger size lesions (2 cm and larger), research is conclusive for high ABR sensitivity; however, for smaller size lesions (1 cm and smaller) research shows contradictory evidence regarding ABR sensitivity.

In a study conducted by Schmidt, Sataloff, Newman, Spiegel, and Meyers (2001), they reported the sensitivity of ABR testing for different lesion sizes. They found a sensitivity of 58% for lesions smaller than 1 centimeter (cm), 94% for lesions 1-1.5 cm, and 100% for lesions larger than 1.5 cm. Zappia, O'Connor, Wiet, and Dinces (1997) reported sensitivity measures of 89% for lesions smaller than 1 cm, 98% for lesions 1-1.2 cm, and 100% for lesions larger than 2 cm. Chandrasekhar, Brackmann, & Devgan (1995) reported ABR sensitivity of 83% for lesions smaller than 1 cm, 100% for tumors 1-1.5 cm, 86% for lesions 1.6-2 cm, and 100% for lesions larger than 3 cm. Gordon & Cohen (1995) reported sensitivities of 69% for lesions smaller than 9 millimeters (mm.), 89% for lesions 1-1.5 cm, 86% for lesions 1.6-2 cm, and 100% for lesions larger than 2 cm.

Recommended Protocol for Neurodiagnostic ABR Testing

Burkard et al. (2007) recommended placing the noninverting electrode on the high forehead, the inverting electrode on the ipsilateral mastoid, and the common or ground electrode on the lower forehead. They also recommended presenting a click stimulus at a level of at least 70 dBnHL. At least 1000-2000 sweeps or averages should be presented.

They also recommended setting the bandwidth filter from 100-3000 Hz and implementing a 10 ms recording window.

Katz (2002) recommended placing the noninverting electrode on the forehead, the inverting electrode on the ipsilateral mastoid, and the common or ground on the contralateral mastoid. He also recommended presenting a click stimulus at a level of 70-90 dBnHL and a rate of 10-20 Hz. At least 1000-2000 sweeps should be presented implementing a 10 ms recording window.

Hall (2006) recommended placing the noninverting electrode on the high forehead, the inverting electrode on the ipsilateral earlobe, and the ground on the lower forehead. He also recommended presenting a click stimulus at a high level at a rate greater than 20/sec to save time and greater than 90/sec to detect retrocochlear dysfunction. He also recommended using a rarefaction polarity at a duration of 0.1 ms. The bandwidth of the filter should be set from 30-3000 Hz, implementing a 15 ms recording window. The number of sweeps performed is variable, depending on the signal-to-noise ratio.

Establishing Norms

Generalized norms are available for ABR test results, but it is important for each audiological clinical facility to develop its own set of standardized norms for each piece of testing equipment. This permits quick and easy identification of abnormal responses. To establish clinical norms, participant factors, stimulus factors, and recording factors must be taken into account. The stimulus and recording parameters must be consistent for each participant tested (Weber, 1992).

Hood (1998b) recommended conducting at least 5 to 10 ABR's on normal hearing participants using the exact same test parameters that are used for neurodiagnostic ABR testing at that facility. This ensures the clinician the equipment is working properly and test results can be converted into normative data and compared to published norms. This also gives the clinician practice using that specific piece of equipment and test parameters.

When establishing norms, a minimum of 10 young adult women and 10 young adult men with normal hearing and no prior history of neurologic or otologic disorders must be tested (Weber, 1992). Sininger (1992) stated that "adult females have shorter peak latencies, larger amplitudes, and shorter interpeak intervals than males. It is recommended that separate norms be established for men and women" (p. 16).

During the development of clinical norms, means need to be determined for the absolute latencies of waveforms I, III, and V, as well as the I-III, III-V, and I-V IPL values. Additionally, standard deviations (SD) must be developed to determine normal from abnormal responses. A +/- 2 SD and/or +/- 2.5 SD range is commonly used to differentiate between normal latency values and abnormal latency values.

Statement of the Problem

The Louisiana Tech University Speech and Hearing Center (LTSHC) is currently implementing ABR testing using published normative data for comparisons. Instrument specific normative data has not been determined for the Nicolet Testing System. Normative date has also not been determined for the local population. This study is important because it provides normative data for this specific testing system which allows for a quick and easy reference for comparing ABR results. This study also provides a set

protocol for identifying retrocochlear pathologies in adult clients who are tested at the LTSHC.

CHAPTER II

METHODS AND PROCEDURES

Participants

Twenty participants, ten males and ten females, between the ages of 18-35 years were selected from the student population of Louisiana Tech University to participate in this study. Each participant signed an informed consent form (see Appendix A) and completed a demographic information form (see Appendix B), which consists of their age, outer and middle ear status, and hearing screening results.

Experimental Procedure

An otoscopic examination was completed bilaterally on each participant with a Welch Allen otoscope. If otoscopy revealed an abnormal ear canal, tympanic membrane, or excessive cerumen the participant was used in this study and appropriate recommendations were made.

Tympanometry, a test of middle ear function, was performed bilaterally using a Grason-Stadler (GSI) TympStar Middle-Ear Analyzer, which is available at the Louisiana Tech Speech and Hearing Center (LTSHC). Normal (Type A) tympanometric tracings are consistent with normal middle ear function. Type A tracings consist of an ear canal volume (ECV) of 0.5 cc.-2.0 cc., static compliance of 0.3 ml.-1.7 ml., and peak pressure of -100 daPa- +100 daPa. If tympanometry results did not meet these criteria, the

participant was not used in this study. Additionally, if an abnormality of the middle ear system was diagnosed the appropriate recommendations were made.

Following otoscopy and tympanometry, a pure-tone hearing screening was administered to each ear. Pure-tone testing was performed using a GSI 61 clinical audiometer, which is available at the LTSHC. Air conduction tones (pulsed, pure tones) were presented through insert earphones (Etymotic Research 3-14A) at all octave frequencies from 250-8000 Hz at 15 dB hearing level (HL). If a participant had a threshold greater than 15 dB HL at any of the octave frequencies tested, they were not used in this study. Additionally, if a participant had thresholds greater than 15 dB HL a full audiological evaluation was completed and appropriate recommendations were made if a hearing loss or abnormalities were present.

Auditory Brainstem Response (ABR) testing was performed with the Nicolet Testing System, which is available at the LTSHC. Each participant was given a description of the testing and all electrode sites were cleaned. Each of the four electrode sites were cleaned thoroughly with an abrasive scrub and alcohol. This was done to ensure that the skin was exfoliated so that the electrodes made contact with the skin and reduced the impedance of the electrical signal. The electrodes were then applied, which consisted of a vertical, two channel, four electrode montage. Disposable surface electrodes (Kendall Soft-E H69P Repositionable Monitoring Electrodes) were used. The inverting (negative) electrodes were placed on the right (A2) and left mastoids (A1). The non-inverting (positive) electrode was placed on the high forehead (Fz) and the ground electrode was placed on the lower forehead (FPz). Inverting and non-inverting electrodes were used to ensure common mode rejection, which increased the likelihood that noise

artifact was cancelled, therefore improving the signal-to-noise ratio. The impedance of each of the electrodes was checked to ensure each electrode connection was no more than 5000 ohms and to ensure that the difference between any two electrodes was no greater than 2000 ohms. If the impedance criteria were not met, each of the electrode sites were examined and the impedance was measured again.

The participant was then instructed to lie down and to relax their muscles and even sleep if possible. The myogenic artifact is lowered the more the muscles are relaxed. When the myogenic noise is reduced, the auditory brainstem responses (ABR) are easier to obtain and are composed of better overall morphology.

Testing was performed by presenting broadband clicks through insert earphones (EAR Link Foam Eartips connected to the Nicolet Model Tip-300 and Nicolet C-300 Cable) to each ear separately. The broadband click stimulus activates a larger frequency region than tone-bursts and therefore provides a more robust ABR waveform. ABR recordings are best obtained at higher intensity levels (70-90 dBnHL) while using slower presentation rates. Therefore, the clicks were presented at 80 dBnHL with a stimulus rate of 19.1 clicks/sec. At least two repeatable waveforms were obtained for each ear. A rarefaction stimulus phase was used for all presentations. A rarefaction stimulus phase provides the greatest chance of clearly identifying wave I of the ABR (Hall, 2006). Additional presentations were given if the morphology of the waveforms was not sufficient enough to label, or the waveforms did not repeat. Artifact rejection was enabled during all recordings. Artifact rejection prevents a response with excessive voltage (myogenic artifact, noise) to be averaged into the overall recording, thus improving the overall signal-to-noise ratio.

All presentations consisted of 1500 sweeps, with no more than 149 sweeps being rejected through artifact rejection (less then a 10% accepted/rejection rate). If greater than a 10% rejection rate occurred on a consistent basis, testing was temporarily stopped and the system was checked for high impedance, excessive external electrical interference, or excessive myogenic potential.

The recording time for each presentation was 10 ms this ensuring proper time window for all waveforms to be recorded. The stimulus duration was 0.1 ms. Research has shown that an ABR is best obtained with a transient or abrupt stimulus (Hall, 2006). The delay time between the stimulus presentation and the recording was 0 ms, meaning that each of the recordings started at the end of the stimulus presentation. Band-pass filtering was utilized in order to increase the signal-to-noise ratio. A high pass filter setting of 100 Hz and a low pass filter setting of 3000 Hz were used for each presentation (reference from filter setting section).

The waveforms were analyzed by the test administrator to determine the absolute latency values of waveforms I, III, and V. All waveforms were marked at the peak of the waveform to ensure that a consistent marking method was used for each participant. Using the absolute latencies, the interpeak latency (IPL) values (I-III, III-V, and I-V) were obtained. Both absolute latency and IPL calculations were made for each ear.

Once all data was collected, the absolutes latencies of waveforms I, III and V for each of the participants were entered into a Microsoft Excel spreadsheet. For each participant there was a total of six entries: the absolute latencies of wave I, III, and V for each ear. Following data entry, the average latency values were calculated for waveforms

I, III and V. Based on these average values and variance, a +/- 2 standard deviation (SD) was calculated.

CHAPTER III

RESULTS

Descriptive Statistics

Age

The average age of the male group was 25.1 years, ranging from 21-34 years of age while the average age of the female group was 24.7 years, ranging from 21-33 years of age. The average age of the total population was 24.9 years.

Male Results

Absolute Latencies

The mean wave I latency value for the male group was 1.58 ms with a range of 0.58 ms (1.38 ms to 1.96 ms). When the two standard deviation value of 0.29 ms is applied to the mean of wave I (1.58 ms), the two standard deviation range for wave I becomes 1.29 to 1.87 ms.

The mean wave III latency value for the male group was 3.78 ms with a range of 0.48 ms (3.54 ms to 4.02 ms). When the two standard deviation value of 0.23 ms is applied to the mean of wave III (3.78 ms), the two standard deviation range for wave III becomes 3.55 to 4.02 ms.

The mean wave V latency value for the male group was 5.53 ms with a range of 0.66 ms (5.28 ms to 5.94 ms). When the two standard deviation value of 0.35 ms is

applied to the mean of wave V (5.53 ms), the two standard deviation range for wave V becomes 5.18 to 5.88 ms.

Interpeak Latencies

The mean wave I-V interpeak latency value for the male group was 2.20 ms with a range of 0.46 ms (1.96 ms to 2.42 ms). When the two standard deviation value of 0.26 ms is applied to the mean of wave I-V interpeak (2.20 ms), the two standard deviation range for wave I-V interpeak becomes 1.94 to 2.46 ms.

The mean wave III-V interpeak latency value for the male group was 1.74 ms with a range of 0.40 ms (1.54 ms to 1.94 ms). When the two standard deviation value of 0.24 ms is applied to the mean of wave III-V interpeak (1.74 ms), the two standard deviation range for wave III-V interpeak becomes 1.34 to1.99 ms.

The mean wave I-V interpeak latency value for the male group was 3.94 ms with a range of 0.64 ms (3.64 ms to 4.28 ms). When the two standard deviation value of 0.38 ms is applied to the mean of wave I-V interpeak (3.94 ms), the two standard deviation range for wave I-V interpeak becomes 3.56 to 4.32 ms. See Table 1 for the male group waveform values described below.

Table 1

Means and 95th Percentile Results for Absolute and Interpeak Latencies in the Male Group

	Mean	SD	95%ile
Absolute Latencies			
Wave I	1.58	0.14	1.87
Wave III	3.78	0.12	4.02
Wave V	5.53	0.18	5.88
Interpeak Latencies			
I-III	2.20	0.13	2.48
III-V	1.74	0.12	1.99
I-V	3.94	0.19	4.32

Female Results

Absolute Latencies

The mean wave I latency value for the female group was 1.60 ms with a range of 0.28 ms (1.48 ms to 1.76 ms). When the two standard deviation value of 0.15 ms is applied to the mean of wave I (1.60 ms), the two standard deviation range for wave I becomes 1.45 to 1.74 ms.

The mean wave III latency value for the female group was 3.75 ms with a range of 0.38 ms (3.60 ms to 3.98 ms). When the two standard deviation value of 0.20 ms is

applied to the mean of wave III (3.75 ms), the two standard deviation range for wave III becomes 3.55 to 3.95 ms.

The mean wave V latency value for the female group was 5.40 ms with a range of 0.68 ms (5.02 ms to 5.70 ms). When the two standard deviation value of 0.41 ms is applied to the mean of wave V (5.40 ms), the two standard deviation range for wave V becomes 4.99 to 5.81 ms.

Interpeak Latencies

The mean wave I-III interpeak latency value for the female group was 2.15 ms with a range of 0.30 ms (2.04 ms to 2.34 ms). When the two standard deviation value of 0.15 ms is applied to the mean of wave I-III interpeak (2.15 ms), the two standard deviation range for wave I-III interpeak becomes 2.00 to 2.31 ms.

The mean wave III-V interpeak latency value for the female group was 1.65 ms with a range of 0.74 ms (1.26 ms to 2.00 ms). When the two standard deviation value of 0.37 ms is applied to the mean of wave III-V interpeak (1.65), the two standard deviation range for wave III-V interpeak becomes 1.28 to 2.02 ms.

The mean wave I-V interpeak latency value for the female group was 3.80 ms with a range of 0.70 ms (3.38 ms to 4.08 ms). When the two standard deviation value of 0.38 ms is applied to the mean of wave I-V interpeak (3.80 ms), the two standard deviation range for wave I-V interpeak becomes 4.00 to 4.19 ms. See Table 2 for the female group waveform values described below.

Table 2

Means and 95th Percentile Results for Absolute and Interpeak Latencies in the Female Group

	Mean	SD	95%ile
Absolute Latencies			
Wave I	1.60	0.07	1.74
Wave III	3.75	0.10	3.95
Wave V	5.40	0.21	5.81
Interpeak Latencies			
I-III	2.15	0.08	2.31
III-V	1.65	0.19	2.02
I-V	3.80	0.19	4.19

Combined Results

Absolute Latencies

The mean wave I latency value for all subjects was 1.59 ms with a range of 0.58 ms (1.38 ms to 1.96 ms). When the two standard deviation value of 0.23 ms is applied to the mean of wave I (1.59 ms), the two standard deviation range for wave I becomes 1.36 to 1.82 ms. Therefore, wave I absolute latencies which are recorded later than 1.82 ms will be considered abnormal and considered as an indicator of a possible retrocochlear pathology.

The mean wave III latency value for all subjects was 3.77 ms with a range of 0.48 ms. (3.54 ms to 4.02 ms). When the two standard deviation value of 0.22 ms is applied to the mean of wave III (3.77 ms), the two standard deviation range for wave III becomes 3.55 to 3.98 ms. Therefore, wave III absolute latencies which are recorded later than 3.98 ms will be considered abnormal and considered as an indicator of a possible retrocochlear pathology.

The mean wave V latency value for all subjects was 5.46 ms with a range of 0.92 ms (5.02 ms to 5.94 ms). When the two standard deviation value of 0.40 ms is applied to the mean of wave V (5.46 ms), the two standard deviation range for wave V becomes 5.06 to 5.86 ms. Therefore, wave V absolute latencies which are recorded later than 5.86 ms will be considered abnormal and considered as an indicator of a possible retrocochlear pathology.

Interpeak Latencies

The mean wave I-III interpeak latency value for all subjects was 2.18 ms with a range of 0.46 ms (1.96 ms to 2.42 ms). When the two standard deviation value of 0.21 ms is applied to the mean of wave I-III interpeak (2.18 ms), the two standard deviation range for wave I-III interpeak becomes 1.97 to 2.39 ms. If a I-III interpeak latency exceeds 2.39 ms it will be considered abnormal and will indicate a possible retrocochlear pathology.

The mean wave III-V interpeak latency value for all subjects was 1.70 ms with a range of 0.74 ms (1.26 ms to 2.00 ms). When the two standard deviation value of 0.32 ms is applied to the mean of wave III-V interpeak (1.70 ms), the two standard deviation range for wave III-V becomes 1.38 to 2.02 ms. If a III-V interpeak latency exceeds 2.02 ms it will be considered abnormal and will indicate a possible retrocochlear pathology.

The mean wave I-V interpeak latency value for all subjects was 3.87 ms with a range of 0.90 ms (3.38 ms to 4.28 ms). When the two standard deviation value of 0.40 ms is applied to the mean of wave I-V interpeak (3.87 ms), the two standard deviation range for wave I-V becomes 3.47 to 4.27 ms. If a I-V interpeak latency exceeds 4.27 ms it will be considered abnormal and will indicate a possible retrocochlear pathology. See table 3 for the male group waveform values described below.

Table 3

Means and 95th Percentile Results for Absolute and Interpeak Latencies in the Combined Group

	Mean	SD	95%ile
Absolute Latencies			
Wave I	1.59	0.11	1.82
Wave III	3.77	0.11	3.98
Wave V	5.46	0.20	5.86
Interpeak Latencies			
I-III	2.18	0.11	2.39
III-V	1.70	0.16	2.02
I-V	3.87	0.20	4.27

CHAPTER IV

DISCUSSION

Purpose

This study was designed to develop normative data for Auditory Brainstem Response (ABR) testing on the Nicolet Testing System. This system is currently being implemented for ABR testing at Louisiana Tech University Speech and Hearing Center. Publicized norms are available; however, research is conclusive that standardized norms should be developed for each testing system and for the local population being tested. Instrument specific normative data has not been determined for the Nicolet Testing System, nor has it been determined for the local population. This study provides a quick and accessible reference guide for determining normal versus abnormal results. It also provides a set protocol for identifying retrocochlear pathologies in adult clients who are tested at the Louisiana Tech University Speech and Hearing Center.

Results

Testing was performed on ten adult males and ten adult females, ranging from 18-35 years of age with normal middle ear function and normal hearing sensitivity. Normative data was developed for the male group, the female group, and for both groups combined (see Tables 1-3).

waveform I was slightly later for the female group compared to the male group. The mean interpeak latencies of all waveforms were slightly later for the male group compared to the female group. This is in agreement with research, which states that males have later latency values than females due to average head size differences.

Published Normative Data

In a study conducted by Musiek, Josey, & Glasscock (1986), using a 80 dBnHL stimulus level and a stimulus rate of 11.3 clicks/sec, they reported mean latency values of 2.05 ms for the I-III IPL, 1.85 ms for the III-V IPL, and 3.88 ms for the I-V IPL. The researchers also reported ±2 SD values of 2.3 ms for the I-III IPL, 2.3 ms for the III-V IPL, and 4.4 ms for the I-V IPL. Additionally, they reported ±2.5 SD values of 2.40 ms for the I-III IPL, 2.45 ms for the III-V IPL, and 4.53 ms for the I-V IPL. See Table 4 for waveform values described below.

Table 4

Musiek, Josey, and Galsscock's Normative Data

	Mean	2SD
Interpeak Latencies		
I-III	2.05	0.25
III-V	1.85	0.45
I-V	3.88	0.52

Antonelli, Bellotto, and Grandori (1987) developed ABR normative data to determine latency and SD values (+2.5 SD values) using a stimulus level of 100 dB peSPL and a stimulus rate of 11 clicks/sec. They reported a mean absolute latency of 1.54 ms with a SD of 1.74 ms for waveform I, 3.73 ms with a SD of 3.98 ms for waveform III, and 5.52 ms with a SD of 4.56 ms for waveform V. This study also reported mean latency values of 2.19 ms with a SD of 2.64 ms for the I-III IPL, 1.79 ms with a SD of 2.42 ms for the III-V IPL, and 3.98 ms with a SD of 4.56 ms for the I-V IPL. See Table 5 for waveform values described below.

Table 5

Antonelli, Bellotto, and Grandori's Normative Data

	Mean	SD
Absolute Latencies		
Wave I	1.54	0.20
Wave III	3.73	0.25
Wave V	5.52	0.96
Interpeak Latencies		
I-III	2.19	0.45
III-V	1.79	0.63
I-V	3.98	0.58

Schwartz, Pratt, and Schwartz (1989), conducted a study to determine normative data for middle-aged adults using a stimulus level of 80 dBnHL and a click stimulus. This study was designed to determine +2.5 SD values. They reported a mean absolute latency of 1.54 ms with a SD of 1.79 ms for waveform I, 3.70 ms with a SD of 4.08 ms for waveform III, and 5.60 ms with a SD of 6.08 ms for waveform V. This study also reported mean latency values of 2.20 ms with a SD of 2.60 ms for the I-III IPL, 1.84 ms with a SD of 2.26 ms for the III-V IPL, and 4.04 ms with a SD of 4.49 ms for the I-V IPL. See Table 6 for waveform values described below.

Table 6

Schwartz, Pratt, and Schwartz's Normative Data

	Mean	SD
Absolute Latencies		
Wave I	1.54	0.25
Wave III	3.70	0.38
Wave V	5.60	0.48
Interpeak Latencies		
I-III	2.20	0.60
III-V	1.84	0.42
I-V	4.04	0.45

Joseph, West, Thorton, & Herman (1987), also conducted a study on ABR normative data for normal hearing adults. They reported mean absolute latencies of 1.65 ms for waveform I, 3.80 ms for waveform III, and 5.64 ms for waveform V. Additionally, the reported mean latency values of 2.15 ms for the I-III IPL, 1.84 ms for the III-V IPL, and 3.99 ms for the I-V IPL. See Table 7 for waveform values described below.

Table 7

Joseph, West, Thorton and Herman's Normative Data

	Mean
Absolute Latencies	
Wave I	1.65
Wave III	3.80
Wave V	5.64
Interpeak Latencies	
I-III	2.15
III-V	1.84
I-V	3.99

Hall (2006) published normative data for 786 nontumor normal hearing adults. He reported mean absolute latencies of 1.65 ms with a 2 SD of 0.28 ms for waveform I, 3.80 ms with a 2 SD of 0.36 ms for waveform III, and 5.64 ms with a 2 SD of 0.46 ms for waveform V. He also reported mean interpeak latency values of 2.15 ms with a 2 SD of 0.28 ms for the wave I-III, 1.84 ms with a 2 SD of 0.28 ms for wave III-V, and 3.99 ms with a 2 SD of 0.40 ms for wave I-V. See Table 8 for waveform values described below.

Table 8

Hall's Normative Data

	Mean	SD	99%ile
Absolute Latencies			
Wave I	1.65	0.14	1.97
Wave III	3.80	0.18	4.22
Wave V	5.64	0.23	6.18
Interpeak Latencies			
I-III	2.15	0.14	2.49
III-V	1.84	0.14	2.16
I-V	3.99	0.20	4.45

Hood (1998b) published normative data for nontumor normal hearing females between the ages of 20-30 years of age, implementing an 80 dBnHL click. She reported mean absolute latencies of 1.62 ms with a 2 SD of 0.24 ms for waveform I, 3.68 ms with a 2 SD of 0.16 ms for waveform III, and 5.47 ms with a 2 SD of 0.24 ms for waveform V. She also reported mean interpeak latency values of 2.06 ms with a 2 SD of 0.22 ms for wave I-III, 1.79 ms with a 2 SD of 0.18 ms for wave III-V, and 3.85 ms with a 2 SD of 0.28 ms for wave I-V. See Table 9 for waveform values described below.

Table 9

Hood's Normative Data

	Mean	SD
Absolute Latencies		
Wave I	1.62	0.12
Wave III	3.68	0.08
Wave V	5.47	0.12
Interpeak Latencies		
I-III	2.06	0.11
III-V	1.79	0.09
I-V	3.85	0.14

The mean data collected for this study compares favorably to the means obtained in the normative data studies listed above. This indicates that the data collected is appropriate for determining the possible presence of retocochlear pathologies during neurodiagnosrtic ABR evaluations. It is again appropriate to note that pathological disorders prolong ABR latencies. As a result, the upper latency limit is determined by applying +2 or +2.5 standard deviations to the mean value. The lower limit of the applied standard deviation range is not used to delineate between a normal auditory system and an auditory system with a retrocochlear pathology. Therefore the 95 percentile (+2 SD) values obtained for the combined group results will be used as the delineation point.

APPENDIX A

HUMAN SUBJECTS PERMISSION FORM

HUMAN SUBJECTS PERMISSION FORM

The following is a brief summary of the project in which you have been asked to participate. Please read this information before signing below:

TITLE: Auditory Brainstem Response (ABR) Normative Data for the Nicolet Testing System.

PURPOSE OF STUDY/PROJECT: The purpose of this experiment is to establish normative data for ABR testing for the Nicolet Testing System, which is used at the Louisiana Tech University Speech and Hearing Center.

PROCEDURES: Each participant will be asked to have an ABR test conducted on them. The participant will be instructed to remain as relaxed as possible and sleep if desired. The testing will be performed by presenting a click stimuli at 70 dB nHL and 90 dB nHL to each ear with a stimulus rate of 19.1 clicks/second. Data will be recorded to determine latency values for waveforms I, III, and V and interpeak intervals I-III, III-V, and I-V for each ear. Results will be entered into a Microsoft Excel spreadsheet for data analysis.

INSTRUMENTS: The subject's identity will not be used in any form in the analysis or representation of the data. Only numerical data such as latency values of waveforms I, III, and V and interpeak intervals I-III, III-V, and I-V for each ear will be used in the presentation of the results.

RISKS/ALTERNATIVE TREATMENTS: There are no known risks to subjects.

BENEFITS/COMPENSATION: Each participant will receive a free audiological evaluation provided by Louisiana Tech Speech and Hearing Center.

I, _____, attest with my signature that I have read and understood the above description of the study, "Sound pressure levels within the ear canal of iPod users," and its purposes and methods. I understand that my participation in this research is strictly voluntary and my participation or refusal to participate in this study will not affect my relationship with Louisiana Tech University and/or Louisiana Tech Speech and Hearing Center. Furthermore, I understand that I may withdraw from the study at any time or refuse to answer any questions without penalty. Upon completion of the study, I understand that the results will be freely available to me upon request. I understand that the results will be confidential, accessible only to the project director, principal experimenters, myself, or a legally appointed representative. I have not been requested to waive nor do I waive any of my rights related to participating in this study.

_____ _____

Signature of Participant Date

CONTACT INFORMATION: The principal experimenter listed below may be reached to answer questions about the research, subject's rights, or related matters.

Matthew Bryan, Au.D., CCC-A Department of Speech (318) 257-3102
Sheryl Shoemaker, Ph.D., CCC-A Department of Speech (318) 257-2146

Members of the Human Use Committee of Louisiana Tech University may also be contacted if a problem cannot be discussed with the experimenters:

Dr. Les Guice	(318)257-4647
Dr. Mary Livingston	(318)257-2292
Nancy Fuller	(318)257-5075

APPENDIX B

DEMOGRAPHICS SHEET

Participant Questionnaire Date: _____

Demographic Sheet

Age: _____

Gender: _____

Otoscopy: _____

Tymponometry:

Ear Canal Volume_____
Static Compliance_____
Peak Pressure_____

Hearing Thresholds (Pass/Fail):

250 Hz_____
500 Hz_____
1000 Hz_____
2000 Hz_____
4000 Hz_____
8000 Hz_____

REFERRENCES

Antonelli, A.R., Belloto, R., & Grandori, F. (1987). Audiologic Diagnosis of Central versus Eighth Nerve and Cochlear Auditory Impairment. *Audiology, 26*, 209-226.

ASHA Working Group. Short Latency Auditory Evoked Potentials: Audiological Evaluation Working Group on Auditory Evoked Potential Measurements.

Ballachanda, B.B., Moushegian, G., & Stillman, R.D. (1992). Adaptation of the Auditory Brainstem Response: Effects of Click Intensity, Polarity, and Postion. [Electronic Version]. *Journal of the American Academy of Audiology, 3*, 275-282.

Bhattacharyya, N., & Scott, M.E. (2006). Auditory Brainstem Response Audiometry. *eMedicine*.

Burkard, R.F., Don, M., & Eggermont, J.J. (2007). *Auditory Evoked Potentials: Basic Principles and Clinical Applications*. Lippincott Williams and Wilkins.

Chandrasekhar, S.S., Brakmann, D.E., & Devgan, K.K. Utility of Auditory Brainstem Response Audiometry in Diagnosis of Acoustic Neuromas. *American Journal of Otolaryngology, 16(1)*: 63-7.

Fowler, C. G. (1992). Effects of Stimulus Phase on the Normal Auditory Brainstem Response. [Electronic Version]. *Journal of Speech and Hearing Research, 35*, 167-174.

Gordon, M.L., & Cohen, N.L. (1995). Efficacy of Auditory Brainstem Response as a Screening Test for Small Acoustic Neuromas. *American Journal of Otolaryngology, 16(2)*: 136-9.

Hall, J.W. III. (1992). *Handbook of Auditory Evoked Responses*. Boston: Allyn and Bacon.

Hall, J. W. III. (2006). *New Handbook of Auditory Evoked Responses*. Boston: Allyn and Bacon.

Hood, L. (1998). Auditory Neuropathy: What is it and what can we do about it? *The Hearing Journal, 51*: 10-18.

Hood, L. (1998). Clinical Applications of the Auditory Brainstem Response. Singular Publishing Group. Clifton Park, N.Y.

Joseph, J.M., West, C.A., Thornton, A.R., & Herrmann, B.S. (1987). *Improved Decision Criteria for Evaluation of Clinical ABR's*. Paper presented at the Biennial meeting of the International Electric Response Audiometry Study Group, Charlottesville, VA.

Katz, J. (2002). *Handbook of Clinical Audiology (5th Ed.)*. Lippincott Williams and Wilkins.

Laws, D., Roller, S., & Perry, C. (1993). Interaural Attenuation of a Click Stimulus Using Deep and Shallow Placement of an Insert Earphone. *American Journal of Audiology*, 60-63.

Musiek, F.E., Josey, A.F., & Glasscock, M.E. (1986). Auditory Brain Stem Response: Interwave Measurement in Acoustic Neuromas. *Ear and Hearing, 7*, 100-105.

Sanchez, J.T., & Gans, D. (2006). Effects of Artifact Rejection and Bayesian Weighting on the Auditory Brainstem Response During Quiet and Active Behavioral Conditions. [Electronic Version]. *American Journal of Audiology, 15*, 154-163.

Schmidt, R.J., Sataloff, R.T., & Newman, J. (2001). The Sensitivity of Auditory Brainstem Response Testing for the Diagnosis of Acoustic Neuromas. *Arch Otolaryngology Head Neck Surgery, 127(1)*: 19-22.

Schwartz, D.M., Pratt, R.E., Jr., & Schwartz, J.A. (1989). Auditory Brain Stem Responses in Preterm Infants: Evidence of Peripheral Maturity. *Ear and Hearing, 10*, 14-22.

Sininger, Y. (1992). Establishing clinical norms for auditory brainstem response. [Electronic Version]. *American Journal of Audiology*, 16-18.

Sininger, Y., & Don, M. (1989). Effects of Click Rate and Electrode Orientation on Threshold of the Auditory Brainstem Response. *Journal of Speech and Hearing Research, 32*: 880-886.

Song, J.H., Banai, K., Russo, N.M., & Kraus, N. (2006). On the Relationship between Speech and Nonspeech-Evoked Auditory Brainstem Responses. [Electronic Version]. *Auditory & Neurotology*, 233-241.

Weber, B. (1992). Patient-specific normative values for auditory brainstem audiometery. [Electronic Version]. *American Journal of Audiology*, 24-26.

Zappia, J.J., O'Connor, C.A., Wiet, R.J., & Dinces, E.A. (1997). Rethinking the use of Auditory Brainstem Response in Acoustic Neuroma Screening. *Laryngoscope, 107 (10)*: 1388-92.