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THE AUDITORY BRAINSTEM RESPONSE (ABR):
A COLLECTION OF NORMATIVE DATA USING THE BIO-LOGIC AEP SYSTEM

by

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THESIS APPROVAL PAGE

This is to certify that the thesis prepared by Tressa Lichtfuss, B.S., Au.D. Candidate entitled The Auditory Brainstem Response: A Collection of Normative Data using the Bio-logic AEP System has been approved by the thesis committee as satisfactorily completing the thesis requirements for the degree Doctor of Audiology (Au.D.).

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ABSTRACT

The Auditory Brainstem Response (ABR): A Collection of Normative Data Using the Bio-logic AEP System

Tressa Lichtfuss

Auditory brainstem response (ABR) normative data was established for the Bio-logic AEP System based on ABR results from 20 normal-hearing, otologically normal individuals between the ages of 20 and 26 years. ABRs were recorded to 100 μs rarefaction click stimuli with a 19.1/sec click rate at intensities 90, 80, and 70 dB nHL for both the left and right ears. Measurements from these recordings included: 1) absolute latencies of waves I, III, and V, 2) interpeak latencies (IPL) of waves I-III, III-V, and I-V, 3) interaural latency differences of wave V and IPL I-V, and 4) wave V/I amplitude ratio. Two additional ABRs were recorded for both the left and right ears; one to a 90 dB nHL condensation click stimulus used to rule out auditory neuropathy spectrum disorder (ANSD), and another to a 90 dB nHL rarefaction click stimulus with an increased click rate (61.1/sec) to observe the effect of click rate on wave V absolute latency.

Results revealed mean absolute latency measurements for waves I, III, and V that decreased by approximately 0.2 ms when intensity decreased from 90 to 70 dB nHL. Mean interpeak latencies for waves I-III, III-V, and I-V remained stable across the same range of stimulus intensities. Interaural differences between wave V and interpeak latency I-V were less than 0.2 ms, indicating that these measurements were nearly

identical between left and right ears. All of the participants had the same ABR waveform polarity in response to a rarefaction and condensation click stimulus. Finally, increasing the click rate from 19.1/sec to 61.1/sec resulted in a mean wave V absolute latency shift of 0.39 ms. All of the measurements obtained in the present study were in agreement with previously reported ABR normative data (Hood, 1998; Beattie, 1988). This equipment-specific data established during the present study will be utilized by students and faculty at the Towson University Hearing and Balance Center when testing patients for retrocochlear pathologies.

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CHAPTER 1: INTRODUCTION

The otologic Auditory Brainstem Response (ABR) is a clinical assessment commonly used to test for retrocochlear pathology (i.e. VIIIth nerve acoustic neuromas). The otoneurologic ABR is elicited with a high-intensity click stimulus and it is recorded with various electrodes placed in different locations on the scalp. It is comprised of five to seven vertex-positive waves that appear approximately 1 to 10 ms after the onset of the click stimulus. The main vertex-positive peaks of the response are waves I, III, and V, and the negative troughs following these main peaks are labeled with a prime (‘) symbol. Various latency and amplitude measurements are taken from the response to assess for retrocochlear pathology.

During the present study, auditory brainstem response (ABR) normative data was established for the Bio-logic AEP System at the Towson University Hearing and Balance Center. Participants included 20 normal-hearing, otologically normal individuals between the ages of 20 and 26 years. A 100 μS rarefaction click stimulus with a 19.1/sec click rate was used to record ABRs at intensities 90, 80, and 70 dB nHL. Measurements from these recordings included: 1) absolute latencies of waves I, III, and V, 2) interpeak latencies (IPL) of waves I-III, III-V, and I-V, 3) interaural latency differences of wave V and IPL I-V, and 4) wave V/I amplitude ratio. A 90 dB nHL condensation click stimulus used to rule out auditory neuropathy spectrum disorder (ANSD), and a 90 dB nHL rarefaction click stimulus with an increased click rate (61.1/sec) was used to observe the effect of click rate on wave V absolute latency. Descriptive statistics (i.e. mean and standard deviation) were calculated separately for the right and left ears for each recording condition. Furthermore, a series of independent t-tests were performed to compare the

mean values of response measurements between the left and right ears. Results of these t-tests indicated that there was no significant difference between any of the right and left ear measurements. Therefore, data from the right and left ears were combined for each of the latency and amplitude measurements.

Results revealed an approximate latency increase of 0.2 ms for mean absolute latency measurements for waves I, III, and V when intensity decreased from 90 to 70 dB nHL that decreased by. Stimulus intensity had no effect on any of the mean interpeak latencies for measurements I-III, III-V, and I-V. None of the participants had interaural latency differences for absolute latency of wave V or of interpeak latency I-V that met or exceeded 0.2 ms. Changing the polarity of the click stimulus from rarefaction to condensation did not result in a reversed ABR waveform polarity for any of the participants. Finally, a mean wave V absolute latency shift of 0.39 ms was observed when click rate increased from 19.1/sec to 61.1/sec. All of the measurements obtained in the present study were in agreement with previously reported ABR normative data (Hood, 1998; Beattie, 1988). This equipment-specific data established during the present study will be utilized by students and faculty at the Towson University Hearing and Balance Center when testing patients for retrocochlear pathologies.

It is imperative that clinics and other facilities that perform ABR testing collect equipment-specific normative data on normal-hearing individuals with a negative otologic history. Measurements that are considered normal on one piece of equipment (e.g., Biologic AEP system) at one facility might not be the same on the same piece of equipment for another facility. This is due to the various factors that can differ between facilities, such as levels of environmental noise or equipment differences. Facilities can

ensure that patient ABR results for certain clinical populations (e.g. young, normal-hearing adults with negative otologic histories) are being compared to accurate normative data specific to their set-up by collecting their own normative ABR measurements.

CHAPTER 2: LITERATURE REVIEW

Auditory Evoked Potentials

An event-related potential (ERP) is defined as an electrical response of the brain that is time-locked to a stimulus (Katz, 2009). The stimulus acts as the "event", while the electrical activity in response to the event acts as the "related potential". Auditory evoked potentials (AEP), a subdivision of ERPs, are defined as recorded electrical activity originating from the peripheral and/or central auditory nervous system (CANS) in response to an acoustic stimulus (Picton, 2011). The acoustic stimuli used in eliciting AEPs can include simple stimuli, such as tone bursts and brief clicks, or more complex stimuli, such as natural or synthetic speech. There are many AEPs that occur in response to acoustic stimuli. Below is a description of several classification systems that have been suggested to describe them.

Classification Schemes of AEPs

One common classification system includes two categories: sensory-evoked potentials (sensory EP) and processing-contingent potentials (PCP) (Katz, 2009). A sensory EP is an obligatory response which occurs in response to an auditory input, as long as the peripheral auditory system and the CANS are intact. Sensory EPs include subcortical and cortical responses evoked from the peripheral hearing organ up to and

including the cortex. The auditory brainstem response (ABR), the middle latency response (MLR), and the slow cortical response (SCR) are all considered sensory EPs. In contrast, PCPs are more complex responses that take place after the obligatory responses have occurred and involve additional cognitive processing. PCPs are strictly cortical in nature, and rely on the brain's attention and perceptual capabilities. For example, a change in the acoustical properties of a stimulus could be used to elicit a PCP. Generally, an oddball paradigm is used to elicit a PCP, where a non-frequent stimulus (i.e., 4000 Hz) is embedded in a string of standard stimuli (i.e., 1000 Hz). In this paradigm, the brain's task is to discriminate between the standard and the non-frequent acoustic stimuli. PCPs include the mismatch negativity (MMN) and late attention-related waves (N2b-P3a/P3b) (Katz, 2009).

Another way to categorize AEPs is by the absolute latency, or the time, in milliseconds, at which they occur after the onset of the stimulus (Picton, 2011). The five categories used to classify AEPs by latency include first, fast, middle, slow, and late responses. Typically, the responses considered "early" are the first and fast AEPs and those considered "late" are the slow and late responses. These five latency categories all occur within 1000 ms post stimulus onset. The first response occurs within 0-5 ms, while the fast response occurs within 1-15 ms. In contrast, the middle response occurs between 10-50 ms and is followed by the slow response (30-500 ms) and the late response (200-1000 ms) (Picton, 2011).

A third method of categorizing AEPs relates to where they occur in the auditory system, or the anatomical structures that generate the response. The first AEPs are thought to be generated by the peripheral auditory system including the cochlea and the

eighth nerve. In contrast, the fast AEPs are generated by the eighth nerve and parts of the brainstem. The middle, slow, and late responses are all considered to be generated by cortical structures (Katz, 2009).

The final classification scheme involves the relationship of the response to the stimulus. Within this scheme, AEPs are considered transient, sustained, or steady-state responses (Katz, 2009). A transient response is only elicited by the onset of a stimulus, while a sustained response remains active throughout the entire length of a repeated or continuous stimulus presentation. A number of AEPs are considered transient responses and these include the ABR, the MLR, and the MMN. Examples of sustained responses include the cochlear microphonic and the frequency following response (FFR) (Hood, 1998). Lastly, steady-state potentials occur when a stimulus is presented at a fast enough rate to cause the response to one stimulus to overlap with the response to the next stimulus within the same post-stimulus analysis window. The auditory steady state response (ASSR) is an example of a steady state response.

The ABR, the primary focus of the current study, is considered a sensory EP according to these classification systems. It is a fast EP that originates from the eighth nerve and parts of the brainstem. In relationship to the stimulus, the ABR is classified as a transient response. The neural generators responsible for the ABR can only be activated by the onset of a stimulus.

In order for audiologists to use the ABR clinically, they need to have a good understanding of the typical morphology of this response and the type of amplitude and latency measurements taken on this response. These properties of the ABR are described below.

Description of the ABR and its Response Measurements

The ABR to a high-intensity click stimulus occurs approximately 1 to 10 ms after the onset of an auditory stimulus. In response to a high-intensity click stimulus, the ABR presents as a series of five to seven vertex-positive waves, as seen in figure 1 below (Hood, 1998). Each of these waves is identified with a designated roman numeral, ranging from I to V (Hood, 1998). The primary peaks in this response are waves I, III, and V. The negative troughs following waves I and V are labeled with a corresponding roman numeral and a prime (‘) symbol. For example, the positive peak wave I is followed by a primary negative trough labeled wave I’ (Picton, 2011).

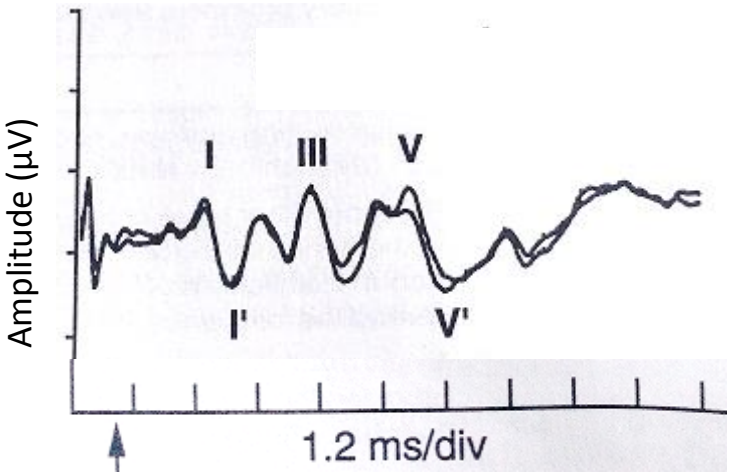

Figure 1. Representation of a normal ABR in response to a 90 dB HL click stimulus

(Hood, 1998)

Various response measurements can be derived from these peaks. Two key response measurements calculated on the ABR are latency measurements and amplitude measurements. Each of these will be described below.

Latency Measurements of the ABR

The latency measurements used for ABR interpretation include absolute latency, interpeak latency intervals (IPL), and interaural latency differences (ILD). Absolute latency is the amount of time in milliseconds between the onset of a stimulus and the occurrence of a peak in the waveform. Typically, absolute latency measurements are calculated on waves I, III, and V. Based on normative data from adults with normal-hearing, ABRs recorded with a 70 dB nHL click stimulus at a rate of 11.1/sec have mean latencies for waves I, III, and V that are 1.69, 3.77, and 5.63 ms, respectively (Picton, 2011). In contrast, IPLs are the time in milliseconds which takes place between two peaks. The three IPLs measured from an ABR waveform are I-III, III-V, and I-V. In response to a 70 dB nHL click stimulus presented at a rate of 11.1/sec to an adult, the mean IPLs for waves I-III and waves III-V are 2.07 and 1.86 ms, respectively (Picton, 2011). In contrast, the mean IPL for wave I-V is 3.9 ms (Picton, 1998). Lastly, the ILD is a measurement which compares the absolute latency of wave V between both ears. An important caveat for this interaural latency comparison is that comparison must be made to the same stimulus presented at the same intensity and same stimulus rate in both ears. This ILD value for wave V should be no more than 0.2 ms in normally-functioning ears (Don & Kwong, 2009). In cases where the ILD is greater than 0.2 ms, the ear with the later wave V latency is suspected of retrocochlear pathology (Selters & Brackmann, 1977). Deviations greater than 2.5 standard deviations from the mean expected absolute

latencies, IPLs, or ILDs could indicate abnormalities or obstructions existing in the auditory pathway (Picton, 2011).

Amplitude Measurements of the ABR

The second important response measurements involve the amplitude of the evoked potential (Hood, 1998). Specifically, a peak-to-peak amplitude measure is calculated for wave I-I' and wave V-V'. In this calculation, the difference in amplitude is measured from the top of the positive peak of these waves to the bottom of the primary negative trough which follows this positive peak. Given the variability that exists in amplitude measurements, the most common diagnostic measurement of amplitude for the ABR compares the peak-to-peak amplitude of wave V-V' to the peak-to-peak amplitude of wave I-I'. This measurement is known as the wave V/I amplitude ratio. Since wave V-V' amplitude is typically larger than wave I-I' amplitude, the wave V/I ratio in a normal auditory system should not be less than one (Hood, 1998). Individuals with a wave V/I ratio less than one could possibly be afflicted by retrocochlear pathology.

Variations in Waveform Morphology

Although the ABR has a general recognizable morphology across individuals, it is rare that one person's ABR is identical to another person's ABR. The differences in waveform morphology of the ABR across individuals typically affect waves IV and V (Hall, 2007). Figure 2 presents four variations in waveform morphology for the ABR often seen across normal-hearing adult subjects. In the figure below, it can be seen that wave IV is riding on the shoulder of wave V and therefore wave V has a larger peak-to-peak amplitude in comparison to wave IV, as seen in the top tracing. In the second

waveform, wave V presents as a single peak with no evidence of wave IV. In contrast, in the third waveform, the amplitude of wave IV is larger than wave V and wave V rides on the outside shoulder of this IV/V complex. Lastly, the final waveform presents a bifid wave IV-V complex. All of these morphologies are normal variations seen in adults with normal hearing sensitivity.

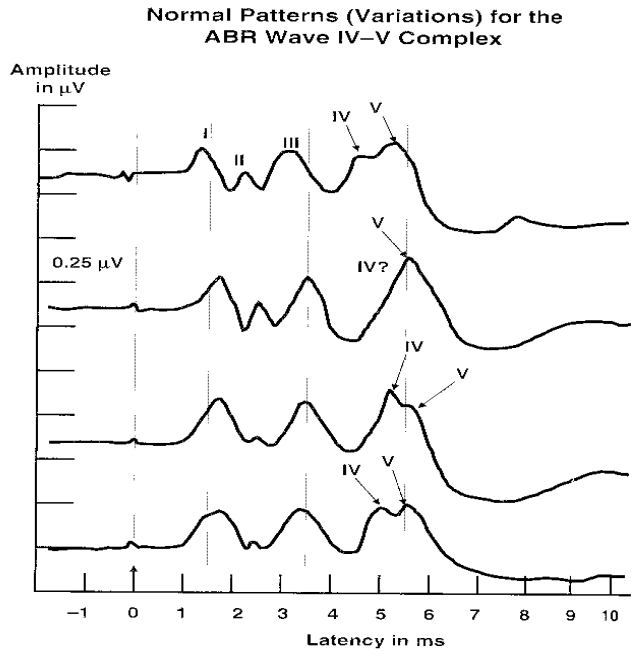

Figure 2. Variations of the ABR in adults with normal hearing sensitivity (Hall, 2007).

Clinical Uses of the ABR

There are two primary clinical uses for the ABR. One use involves threshold-seeking to estimate the client's behavioral hearing sensitivity at various test frequencies (Picton, 2011). This method of examining hearing is often used in individuals who are unable to participate in behavioral testing, such as infants and intellectually disabled individuals. The other commonly used clinical purpose for the ABR is to determine the integrity of the auditory pathway, otherwise known as otoneurologic testing. An ABR

recorded for otoneurologic purposes is observed for any anomalies that may indicate an obstruction of the auditory pathway by a pathology such as a tumor. An ABR is often recommended for individuals who are suspected of having retrocochlear pathology (Picton, 2011). Oto-neurologic ABRs will be the focus for the current paper.

In order to fully understand the ABR and its clinical value, audiologists need to be familiar with the underlying neural generators of this response. This topic will be discussed in the next section.

Generators of the ABR

The ABR is generated by multiple neural sources within the auditory pathways. The sources that produce electrical energy in response to an auditory stimuli are known as neural generators (Moller, 1998). There are two leading methods used to study the neural generators of the ABR. One such technique involves severing individual nuclei or nerve tracts of the afferent auditory pathway to observe how the morphology of the scalp-recorded ABR is affected. This method can easily be utilized in animal subjects, but can only be implemented in humans who have pre-existing lesions within the hearing system. The second method involves comparing intracranial latencies of electrical potentials that are directly recorded from a single structure within the auditory pathway (such as the cochlear nucleus) to the surface-recorded latencies and amplitudes of the ABR waves. Intracranial potentials generated with latency measurements similar to those found in the scalp-recorded ABRs are thought to represent energy from at least one underlying neural generator source for that particular peak (Moller, 1998).

Over the past three decades, these two primary methods have been utilized in animals and humans to determine the anatomical structures that contribute to the ABR. Most often, the animals used in these studies have been cats (Moller, 1998). In humans, the entire VIII nerve has been measured to be 30 mm from the cochlea to the cochlear nucleus, while the length of the VIII nerve in cats has been measured to be only 3 mm (Starr, 1990). This difference in length between species causes absolute latency measurements and the number of peaks to differ between the two species. For example, the ABR of a cat includes five to six vertex-positive waves (labeled P1-P6), with P4 being the largest in amplitude. In contrast, humans exhibit six to seven vertex-positive waves, with Wave V being the most prominent (Starr, 1990). With these differences in mind, the preliminary research using cats provides substantial information on how the human auditory system processes sound, and thus will be reviewed first below.

Neural Generators of the ABR in Animals (Cats)

Jewett (1970) observed the ABR in 18 anesthetized cats to determine where in the auditory system each peak of the waveform originated. In this experiment, Jewett recorded ABRs using near-field recordings with the active electrode located on the round window of the cochlea and the reference electrode located on the cat's tongue. He then varied the placement of the recording electrodes to determine the effect on each individual peak. He reported that wave P1 had the largest amplitude when recorded from the VIII nerve, wave P2 was largest when recorded from the cochlear nucleus, and wave P3 was largest when recorded from the superior olivary complex. Lastly, waves P4 and P5 were most prominent when recorded in proximity to the inferior colliculus.

Starr (1990) further examined neural contributions to the early components of the ABR in cats. Starr recorded electrical potentials at four different locations along the VIII nerve and compared the latencies of these responses to those obtained from the scalp-recorded ABR. He first recorded an ABR between the vertex of the scalp and the neck, and noted that this electrode montage sectioned wave P1 into two positive peaks named P1a and P1b. Starr reported that the more distal portions of the VIII nerve, such as the intracochlear portion, had electrical potentials that temporally coincided with the P1a latency of the ABR. In contrast, more proximal locations, such as where the VIII nerve meets the cochlear nucleus, had electrical potentials that were more temporally similar to wave P1b. This data suggests that, in the cat, wave P1a of the ABR occurs when there is activity in the cochlear portion of the VIII nerve. On the other hand, the second component of P1 occurs due to activity arising later, where the VIII nerve joins the cochlear nucleus.

To further investigate neural generators for the ABR in cats, Buchwald and Huang (1975) made surgical lesions in the auditory pathways of 10 cats to determine the effect of these lesions on the ABR recordings. A series of control ABRs were recorded first in the absence of lesions. The first lesion was made by severing the brainstem above the level of the inferior colliculi. Then, the inferior colliculi was either removed or severed. Next, the cochlear nucleus was surgically separated from the brainstem, and lastly the VIII nerve was severed at the level of the internal auditory canal.

A series of ABRs were recorded following each new lesion, with at least one hour between recordings. Buchwald and Huang (1975) reported that the waveform morphology of the ABR remained intact after separating the inferior colliculi from the

more rostral regions of the brain. However, when the lesion included the inferior colliculi or separated it from the rest of the auditory pathway, wave V was eliminated from the ABR. Hence, these authors concluded that the inferior colliculi generates electrical activity relating to wave V in a typical ABR recording. A lesion of the cochlear nucleus caused waves III and IV to diminish, indicating that the cochlear nucleus is needed to elicit these waves. Lastly, after the VIII nerve was separated from the cochlear nucleus, wave II disappeared but wave I remained, indicating that this anatomical site is the primary generator of wave II.

In summary, the collective results of neural generator studies in animals provided the basis for which the results of neural generator studies in humans could be interpreted. These human generator studies will be discussed in the next section.

Neural Generators of the ABR in Humans

Starr (1976) recorded ABRs in individuals with confirmed brain lesions mainly caused by tumors, strokes, or anoxia which affected the integrity of their brainstems. Starr (1976) reported that individuals with lesions affecting the midbrain, particularly the inferior colliculus, presented with absent or abnormal waves IV-VII. Conversely, in patients where the entire brainstem was affected all of the ABR waves were affected except for wave I. In general, these findings were in agreement with the animal studies performed by Starr (1990) and Buchwald and Huang (1975). Collectively, these results suggest that wave I depends on the integrity of the intracochlear auditory nerve, while Wave II is reliant on the more proximal portion of the VIII nerve. When lesions included the cochlear nucleus, the trapezoid body, or the superior olive, Waves II and III were both affected.

Moller and Jannetta (1982) recorded electrical potentials from the inferior colliculus in individuals undergoing neurosurgery and compared the results to typical scalp-recorded ABRs. The ABRs for both the intracranial and surface recordings were measured to a 2000 Hz tone burst. These investigators reported that the inferior colliculus produced a slow negative potential temporally similar to the latency of wave V of the contralateral ABR recording. The wave elicited by the inferior colliculus had an absolute latency of about 7.0 ms, while wave V of the scalp-recorded ABR had an absolute latency of about 6.5 ms. A positive peak occurred prior to the slow wave, at almost the same point in time as wave V of the ABR. These results provided evidence that in humans, the inferior colliculus is a primary contributor to later components of the ABR, particularly to wave V.

Moller and Jannetta (1983) ran a second experiment similar to their initial study on the inferior colliculus, but instead took recordings from the cochlear nucleus and compared them to measurements from scalp-recorded ABR waves. The cochlear nucleus potential measured with an ipsilateral stimulus was comprised of a prominent surface-negative component. This component had a latency that most closely resembled wave III of the scalp-recorded ABR. Therefore, the authors concluded that the cochlear nucleus generated energy that was responsible for wave III of the ABR in humans.

Collectively, findings from these animal and human studies suggest that wave I is generated by the distal portion of the VIIIth nerve, wave II is generated by the more proximal portion of the VIIIth nerve, waves III and IV are generated primarily by the cochlear nucleus and superior olivary complex, and wave V is primarily generated by the

lateral lemniscus and inferior colliculus. Waves III and V receive contributions from multiple sources in the auditory brainstem.

The ABR can be elicited from these various neural generators by presenting an auditory stimulus, such as a high-intensity click, to the auditory pathway. There are multiple technical parameters involved in obtaining an ABR that can have an impact on the recording. These technical parameters will be described in detail in the following section.

Technical Parameters

The technical parameters used to record the auditory brainstem response can have a dramatic effect on the integrity and accuracy of the response being recorded. These technical parameters include stimulus parameters, recording parameters and subject-related parameters. A brief discussion of how stimulus parameters such as the type of stimulus, stimulus rate, stimulus intensity, and stimulus polarity affect the ABR will be provided in this next section of the literature review.

Stimulus Parameters

Stimulus Type.

The two most commonly utilized stimuli used to record the ABR are clicks and tone bursts (Hall, 2007; Sininger & Hyde, 2009). A click stimulus, presented through a supra-aural earphone, is characterized by a wide range of spectral energy present between 100 Hz and 10,000 Hz (Picton, Stapells & Campbell, 1981). Figure 3 depicts the flat, wide frequency response which is present with both a rarefaction and a condensation click stimulus. As can be seen in the figure, a solid block of energy is present from 100

Hz up until 10,000 Hz, where the energy quickly tapers off. The range of energy present in the click stimulus is independent of stimulus polarity (Picton et al., 1981).

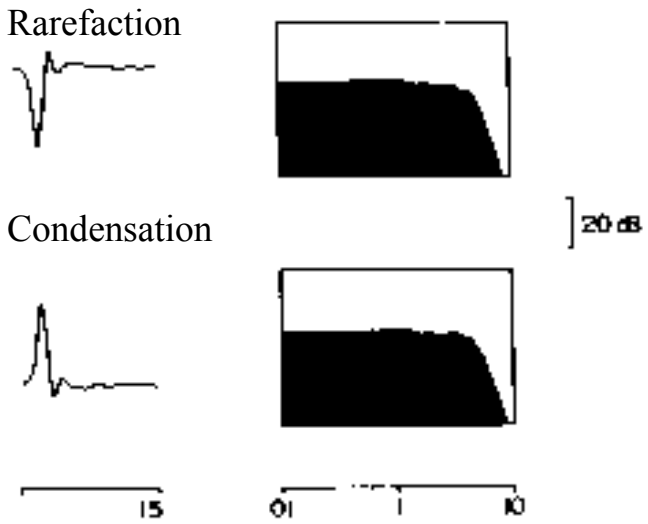

Figure 3. Two graphs displaying the spectral energy present in a rarefaction and condensation click stimulus. (Picton, et al., 1981).

The duration of the click stimulus is typically 100 microseconds (µsec). Due to its broad spectral energy and its short duration, a click stimulus presented at a moderate to high stimulus intensity elicits a response from a very broad region of the basilar membrane (Hood, 1998). The click stimulus is typically used for otoneurologic purposes due to the robust response elicited from multiple areas of the cochlear partition (Hall, 2007).

In contrast, a tone burst stimulus has a more narrow spectral energy which is centered around the primary frequency of the stimulus (Picton et al., 1981). There are also side lobes of energy that occur above and below the main frequency of the stimulus. Figure 4 provides a representation of the main peak of energy in a 500 Hz tone burst stimulus. Side lobes of energy can be viewed on either side of the main peak of energy.

These side lobes contain a lower amount of energy in comparison to that seen in the peak area. Since tone burst stimuli are more frequency-specific in comparison to click stimuli, tone bursts are the stimuli of choice for threshold-seeking ABRs in order to predict/estimate the pure tone audiogram (Sininger & Hyde, 2009).

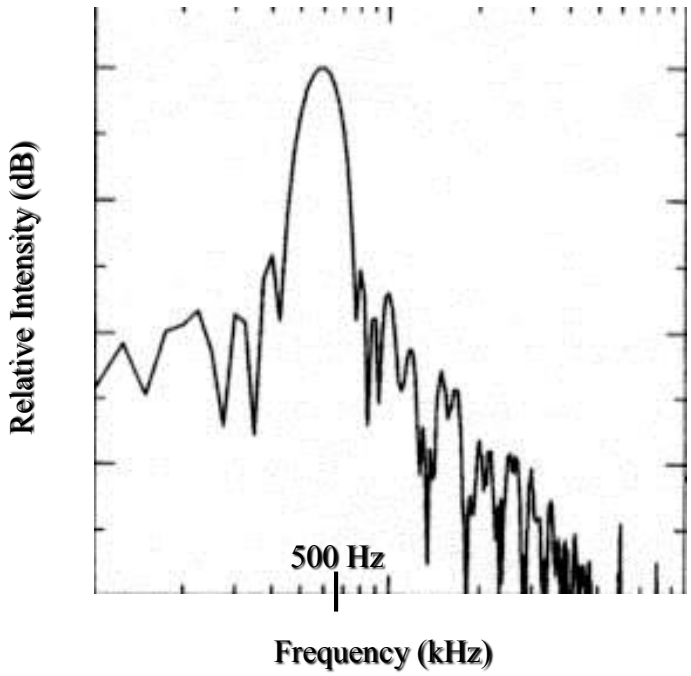

Figure 4. Spectral energy present in a 500 Hz tone burst stimulus (Picton et al., 1981).

Since the focus of the current study is collecting normative ABR data for otoneurological purposes, high intensity click stimuli presented at levels of 70, 80 and 90 dB nHL will be employed. The ABR recorded to a high-intensity click stimulus consists primarily of waves I, III, and V (Hood, 1998). Therefore, latency and amplitude

measurements can be taken on these peaks and compared to normative data to determine if any abnormalities exist.

Stimulus intensity.

Stimulus intensity is the term used to characterize the level at which a stimulus is presented and is reported in decibels per normal hearing thresholds (dB nHL). Stimulus intensity has been shown to have an effect on latency measurements, peak-to-peak amplitudes, and overall morphology (Don, Allen, & Starr, 1977; Wolfe, Skinner & Burns, 1978). It is important to understand these effects so that an appropriate stimulus intensity level may be selected for recording the otoneurologic ABR.

There has been an overall trend reported in the literature that as stimulus intensity is decreased, absolute latencies increase for all ABR waves. (Don et al., 1977; Wolfe et al., 1978). Don, Allen, and Starr (1970) assessed the effects of stimulus intensity on the latency of wave V of the auditory brainstem response. Click-evoked auditory brainstem responses were elicited from six normal-hearing young adults at the following stimulus intensity levels: 30, 40, 50, and 60 dB sensation level (SL). The researchers found that for every 10 dB SL decrease in stimulus intensity, wave V had about a 0.4 ms increase in absolute latency. Figure 5 displays ABR waveforms in response to click stimuli that are decreased in intensity from 80 dB nHL to 10 dB nHL. Note the latency increases for wave V with every 10 dB nHL decrease of stimulus intensity.

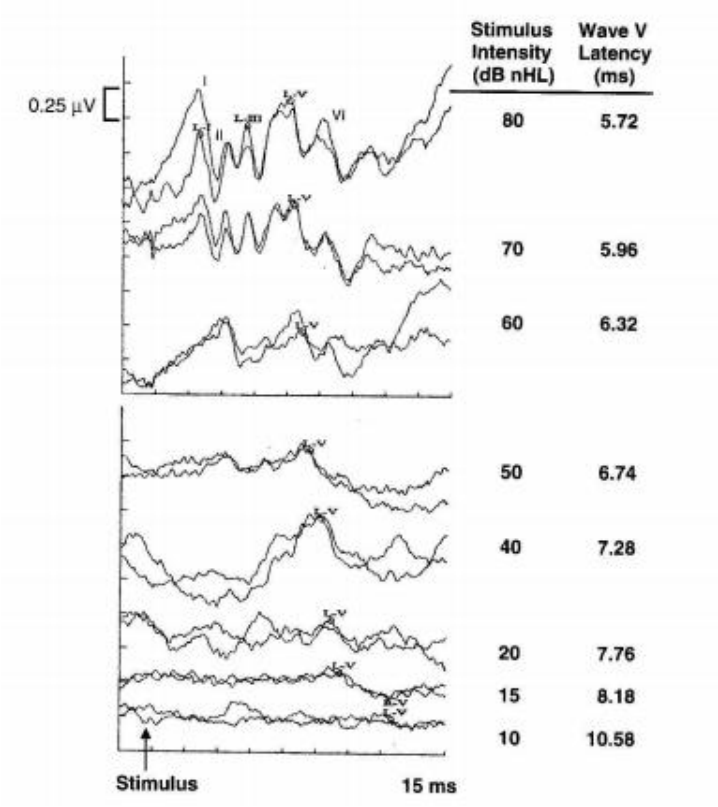

Figure 5. – Auditory brainstem response waveforms elicited with click stimuli descending in intensity from 80 down to 10 dB nHL (Hall, 2007).

Wolfe, Skinner, and Burns (1978) also assessed latency shifts of the ABR due to changes in stimulus intensity. These researchers recorded click-evoked ABRs using seven different intensities in five adults with normal hearing. The intensities used for the recordings were 15, 20, 30, 40, 50, 60, and 70 dB SL. Wolfe and colleagues reported that the absolute latency measurements for waves I through V of the ABR increased with each 10 dB SL decrease in intensity down to 20 dB SL. Wave V latency appeared to increase the most in response to decreasing the stimulus intensity. For example, the difference in wave V latencies between the two intensities 60 and 20 dB SL was 1.69 ms, while the difference between wave I latencies for the same intensity levels was only 0.45 ms.

Stimulus intensity has also been reported to affect the peak-to-peak amplitude of all the ABR waves. Wolfe et al. (1978) reported that the early components of the ABR (waves I and III) were either absent or too variable and inconsistent between subjects when elicited at stimulus intensities less than 50 dB nHL. In contrast, these authors reported that the mean wave V-V' amplitude decreased from 0.35 μV for the 70 dB SL test condition to 0.21 μV, for the 20 dB SL condition.

Since waves I through III are often absent or decrease in amplitude at lower stimulus intensities, a decrease in stimulus intensity causes the overall morphology of the ABR to become flatter and wave V is often the only identifiable wave at these low intensities (Wolfe et al., 1978). Since the amplitude of wave V is least affected by stimulus intensity, wave V is routinely used for threshold-seeking purposes. However, an otoneurologic ABR must be obtained with high-intensity clicks so that a clear waveform morphology with identifiable peaks I, III and V can be used to take necessary measurements.

In summary, decreasing the intensity of the click stimulus produces latency shifts, decreased peak-to-peak amplitudes and changes in the overall morphology of the ABR. These morphological changes may include the absence of the early waves I and III, as well as a broader shape for wave V at the lower stimulus intensities (Wolfe et al., 1978). For these reasons, the click stimulus will be presented at high stimulus intensities (i.e., 70, 80, and 90 dB nHL) in the proposed study in order to record robust waves I, III and V peaks to use for determining normative data for otoneurologic purposes.

Stimulus Rate.

The rate at which a stimulus is presented can have an impact on the absolute latency, peak-to-peak amplitude measurements, and the overall morphology of the ABR (Hall, 2007; Picton et al., 1981; Yagi & Kaga, 1979). The rate of a stimulus is defined as the number of stimuli presented in a one second period of time (Picton et al., 1981).

According to Picton, Stapells and Campbell (1981), stimulus rate affects latency measurements differently for the various components of the ABR. Specifically, wave V is more impacted by stimulus rate than wave I. For example, when click rate is increased from 10 to 80/sec, wave V undergoes a latency increase of about 0.39 ms. In contrast, wave I latency is reported to increase only by 0.14 ms when click rate is increased from 10 to 80/sec. A visual representation of the mean latencies recorded for the six different click rates can be observed in figure 6 (Yagi & Kaga, 1979). This figure demonstrates the following findings: mean latencies from slower click rates are shorter than mean latencies from faster click rates, and the effect of stimulus rate on ABR latencies is most prominent on wave V. For example, mean absolute latencies for waves I and V elicited with a 5/sec stimulus rate were 0.23 and 0.61 ms shorter than when they were elicited with a 90/sec stimulus rate, respectively. This finding indicates that increasing stimulus rate has more of an impact on central components of the auditory pathway than it does on peripheral components (Hall, 2007; Yagi & Kaga, 1979).

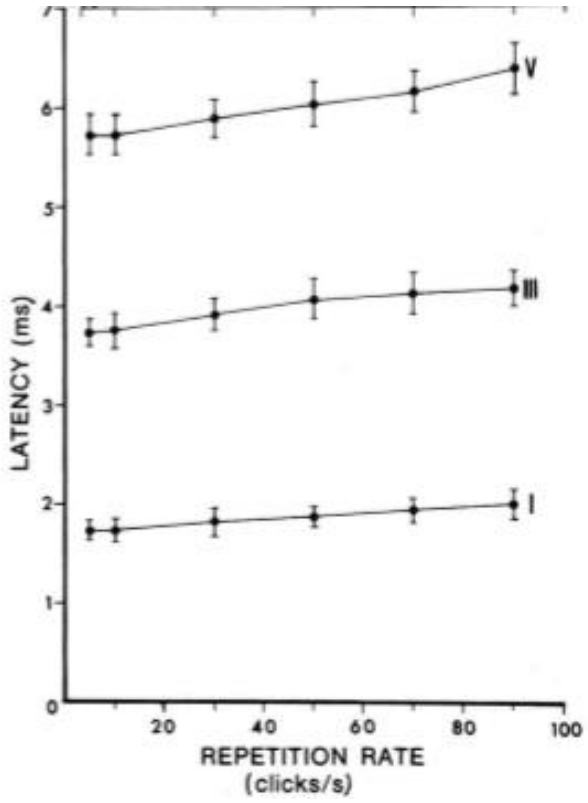

Figure 6. Line graph depicting effects of varying stimulus rates on waves I, III and V of the ABRs in 11 normal-hearing young adults. The six stimulus conditions were rates of 5, 10, 30.3, 50, 71.4, and 90/sec. The stimulus intensity was 70 dB SL for all recording conditions (Yagi & Kaga, 1979).

In contrast, the opposite is seen regarding rate effects on amplitude, where earlier components (waves I and III) of the ABR are more strongly affected than later components (wave V) (Hall, 2007; Picton et al., 1981). When rate is increased from 10 to 80/sec, amplitude of waves I and III decrease by about 50%, while amplitude of wave V only decreases by about 10 to 15%. Picton and colleagues also reported that amplitudes of waves I and III begin to decrease at click rates > 20/sec. Thus, in order to preserve the peak to peak amplitudes of wave I in the proposed study, a stimulus rate of 19.1/sec will be employed.

A stimulus rate > 20/sec also has an impact on the morphology of the earlier ABR components. Often, stimuli with click rates above 20/sec elicit ABRs with decreased or absent waves I and III, causing these early components to be difficult to identify (Hood, 1998; Picton et al., 1981). Figure 7 below demonstrates these morphology changes as a function of increasing click rate. Since waves I and III are imperative components of the otoloneurologic ABR, a click rate < 20/sec should be utilized.

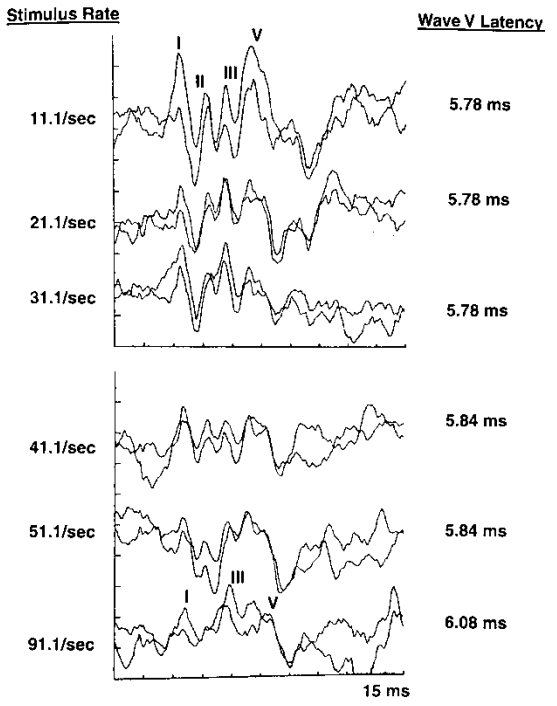

Figure 7. ABR responses as a function of progressively increasing click rate from 11.1 to 91.1/sec (Hall, 2007).

Comparing the shifts in wave V latency from a slower rate (i.e., 19.1/sec) to a faster stimulus rate (i.e., 61/sec) has been found to be clinically useful in identifying more subtle auditory neuropathology when recording an otoneurologic ABR (Hall, 2007; Picton 1998). This is likely because faster stimulus rates cause the auditory system to be

taxed beyond its natural capacity. An abnormal increase in latency or complete disappearance of wave V in response to an increased stimulus rate has been reported to be indicative of retrocochlear pathology (Daly, Roeser, Aung, & Daly, 1977; Hall, 2007). Therefore, it is important to employ a faster stimulus rate in conjunction with a slower click rate when conducting an otoneurologic ABR.

For the purposes of the proposed study, we will be using stimulus rates of both 19.1 and 61.1/sec. The 19.1/sec rate will be used to elicit robust waves I, III and V measurements, while the 61.1/sec rate will be used to determine normal latency and amplitude variations in response to increased click rate.

Stimulus polarity.

The auditory brainstem response can be elicited with a rarefaction or a condensation stimulus. A rarefaction stimulus pulls backward on the tympanic membrane, causing a positive deflection of the basilar membrane to take place that results in neural firing (Mauer, Schafer, & Leitner, 1980). In contrast, a condensation stimulus causes a forward push on the tympanic membrane, which in turn produces a negative deflection of the basilar membrane, delaying the onset of neural firing (Maurer et al., 1980).

These two different stimulus polarities have been shown to cause latency and amplitude differences in certain components of click-evoked auditory brainstem response recordings (Emerson, Brooks, Parker, & Chiappa, 1982; Fowler, Bauch, & Olsen, 2002; Maurer et al., 1980). Emerson et al. (1982) recorded ABRs to both rarefaction and condensation click stimuli in 45 normal-hearing adults to investigate the effects of

stimulus polarity on the click-evoked ABR. These stimuli were presented monaurally at a rate of 10 clicks per second and at an intensity level 70-80 dB SL. The mean peak-to-peak amplitude of wave I-I ' was reported to be consistently larger for a rarefaction click versus a condensation click in these subjects. Specifically, the mean wave amplitude of wave I-I' was 0.29 μV for the rarefaction click stimulus and 0.21 μV for a condensation click stimulus. In contrast, the reverse trend occurred for wave V. The mean wave V amplitude was larger for the condensation versus rarefaction click stimuli (0.45 μV versus 0.39 μV). Emerson and colleagues also reported that the mean wave I absolute latency was 0.05 ms shorter when elicited with a rarefaction click stimulus than with a condensation click stimulus. There were no significant differences in the absolute latencies of waves III and V as a function of stimulus polarity.

In a similar study, Maurer et al. (1980) examined the latency and amplitude differences in ABRs recorded to the two stimulus polarities in 14 normal-hearing adult subjects. The ABRs were recorded to an 80 dB nHL tone burst stimulus presented at a rate of 10 pips per second. Maurer and colleagues reported that the mean peak-to-peak amplitudes for wave I-I' were larger for the rarefaction versus condensation stimuli with the opposite effect seen for wave V amplitudes (i.e., larger peak-to-peak wave V amplitudes for the condensation versus rarefaction tone bursts). These investigators also reported that mean absolute latencies for wave I were earlier for the rarefaction stimuli than the condensation stimuli. These results were in good agreement with the findings of Emerson et al. (1982).

The latency difference between wave I in rarefaction and condensation recording conditions is said to be related to the initial displacement of the basilar membrane in

response to the stimulus (Salomon & Elberling, 1971; Fowler, Bauch, & Olson, 2002). As mentioned previously, a rarefaction stimulus causes an outward movement of the tympanic membrane and the stapes footplate to occur, which in turn causes the basilar membrane to deflect upward. This upward motion of the basilar membrane causes depolarization within the cochlea that initiates neural firing. In contrast, a condensation stimulus pushes the tympanic membrane forward so that an inward movement is achieved, which instead causes a downward deflection of the basilar membrane. Neural firing does not occur until the basilar membrane is displaced in an upward motion, which is why the latency for wave I in response to a condensation stimulus is delayed (Salomon & Elberling, 1971; Fowler et al., 2002).

Figure 8 displays ABRs elicited to rarefaction and condensation click stimuli at a 60 dB nHL intensity level. Several interesting effects of stimulus polarity can be seen. First, wave I has a larger peak-to-peak amplitude in response to the rarefaction stimulus in comparison to the condensation click stimulus. Secondly, the amplitude of wave V-V' is larger to a condensation click than when evoked to a rarefaction click. Lastly, wave IV and V are clearly separated when elicited with rarefaction click, while they appear to be merged when elicited with a condensation click.

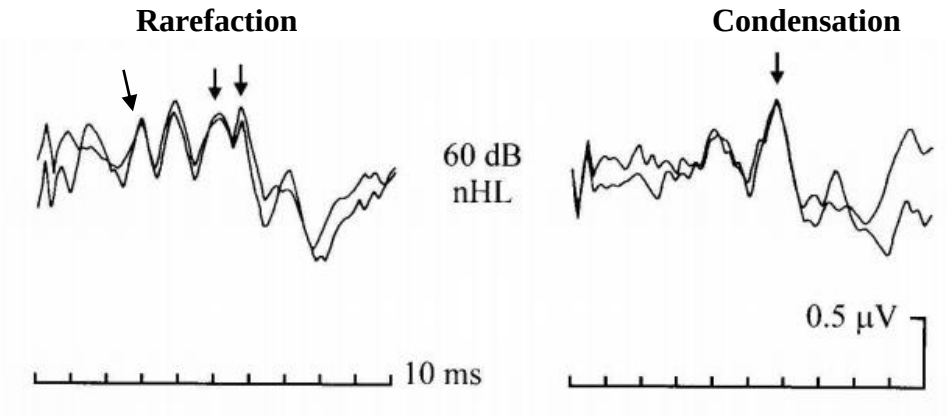

Figure 8. ABRs recorded to rarefaction and condensation stimuli at 80 dB nHL and 60 dB nHL intensity levels (Picton, 2011).

During the recording of an otoneurologic ABR, audiologists typically record the ABR separately to a rarefaction click and a condensation click at the same stimulus intensity in order to rule in or rule out Auditory Neuropathy Spectrum Disorder (ANSD). ANSD is a hearing impairment characterized by present otoacoustic emissions and/or a present cochlear microphonic, as well as an absent or abnormal ABR (Norrix & Velenovsky, 2014; Shi et al., 2012). These findings typically indicate a healthy, functional cochlea in the presence of an impaired auditory nerve. In ANSD, this impairment of the auditory nerve causes a distorted signal to be sent to the brain for processing.

Since the integrity of the cochlea is typically preserved in cases of ANSD, a pre-neural sinusoidal waveform, known as the cochlear microphonic, often appears when recording an ABR (Hood, 1998). This waveform reflects the physical traveling wave of the basilar membrane elicited by an auditory stimulus. Therefore, when the polarity of the stimulus is changed from condensation to rarefaction, this reversal in stimulus polarity is

reflected in the CM waveform (Norrix & Velenovsky, 2014). The cochlear microphonic in response to a condensation stimulus should be negative in polarity, while a rarefaction stimulus should elicit a positive waveform. By using both a condensation and rarefaction stimulus to elicit the ABR, a reversal in polarity can help differentiate a cochlear response from a neural response (Shi et al., 2012).

Below, Figure 9 portrays a normal ABR in response to a condensation click and a rarefaction click, as well as the summed formation of both ABR tracings. In this figure, the cochlear microphonic can be seen to reverse in polarity when the stimulus is changed from a condensation click stimulus to a rarefaction click stimulus, while the following ABR neural response (waves I-V) maintains a positive polarity in response to both stimuli. When the two waveforms are summed, the cochlear microphonic is canceled out and ABR waves I-V remain, indicating a true neural response.

In contrast, figure 10 portrays an absent ABR with a present cochlear microphonic in response to a condensation click stimulus and a rarefaction click stimulus. Reversal in polarity can be observed for the entire response (CM plus ABR) when the polarity of the stimulus changes from rarefaction to condensation, indicating that the ABR waves are not a neural response. The summed waveform of the rarefaction response and the condensation response reveals a flat line, as both responses cancel each other out due to having opposite polarities. This finding is typical in individuals with ANSD (Hood, 1998). Therefore, using both a rarefaction and a condensation stimulus to record the ABR is common practice in diagnosing ANSD.

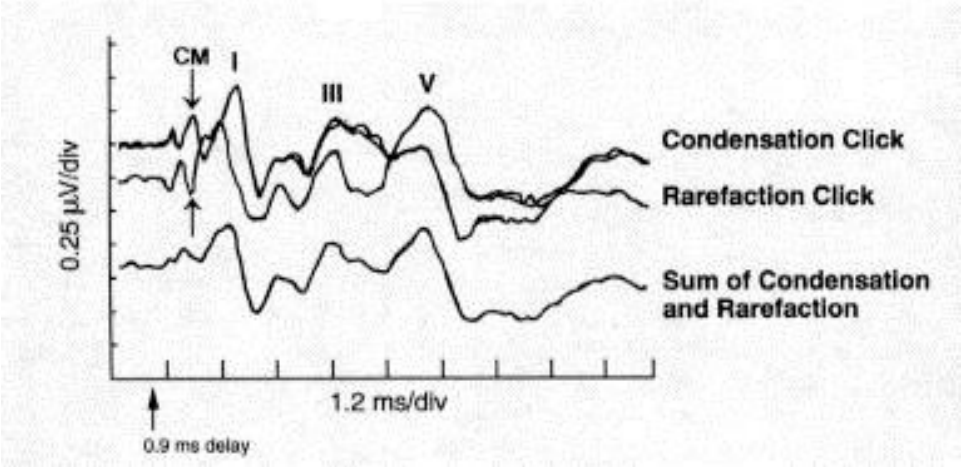

Figure 9. Normal ABR in response to a condensation click stimulus and a rarefaction click stimulus, as well as the summed formation of both recordings. CM = cochlear microphonic (Hood, 1998).

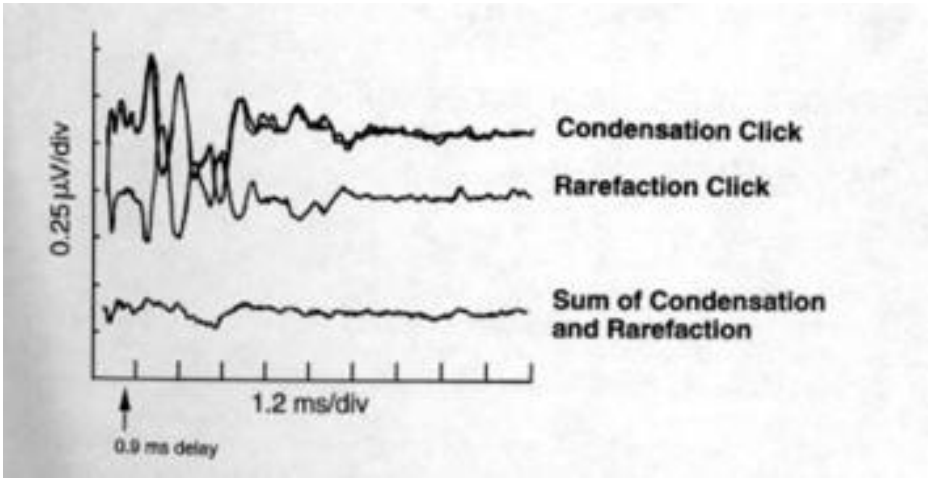

Figure 10. Absent ABR in response to a condensation click stimulus and a rarefaction click stimulus, as well as the summed formation of both recordings. The summed formation is a flat tracing, indicating that neither the condensation stimulus nor the rarefaction stimulus elicited a neural response (Hood, 1998).

For the purposes of the proposed study, a rarefaction polarity will be used to record initial ABRs due to its ability to elicit a larger wave I-I' amplitude and overall shorter absolute latencies (Maurer et al., 1980; Emerson et al, 1982). Additionally, a separate recording of the ABR to a condensation polarity click stimulus presented at 90 dB nHL will be obtained. The 90 dB nHL responses to the rarefaction and condensation stimuli will be compared to rule out ANSD for the participants taking part in the proposed study.

Recording Parameters

The specific recording parameters selected by the audiologist can impact the integrity and accuracy of the ABR. These recording parameters include: the electrode montage and number of recording channels; the analog band-pass filter setting; the number of sweeps contributing to the average waveform; the artifact rejection level; differential amplification and common mode rejection; and the length of the post-stimulus analysis window. Each of these recording parameters are briefly described below.

Electrode Montage and Number of Recording Channels.

Electrode montage refers to the locations on the scalp where recording electrodes are placed. The locations most commonly used for ABR recordings include: Fz (forehead), A1 (left earlobe), A2 (right earlobe), and Cz (vertex) (Hood, 1998; Klem, Lüders, Jasper, & Elger, 1999). The uppercase letters F, A, and C represent the anatomical scalp locations frontal, auricular, and coronal, respectively (Klem et al., 1999). The typical electrode montage for ABR recordings includes: placing the

noninverting electrode on the vertex (i.e., Cz); the inverting electrodes on both earlobes; and the ground electrode on the forehead. When the inverting electrode is located on the ear which receives the stimulus, this is known as an ipsilateral recording. When the inverting electrode is located on the non-stimulus ear, this is considered a contralateral recording (Hood, 1998). Occasionally the midline electrode has been placed on Fz rather than Cz in cases such as testing infants (Picton, Durieux-Smith, Edwards, & McMurray, 1985). This is due to concern about placing an electrode near the location of the fontanel region. In adults, although there are minimal differences between recordings taken from sites Fz and Cz, there have been reports that wave V amplitude decreases when the inverting electrode is placed on the high forehead (Fz) (Beattie, Beguwala, Mills, & Boyd, 1986; Hall, 2007). Therefore, in order to obtain the most robust wave V response, the vertex (Cz) will be utilized as the site for the noninverting electrode in the proposed study.

The ABR is typically recorded using either one or two recording channels (Hood, 1998, Picton, 2011). A single-channel recording allows for only an ipsilateral ABR to be obtained. A two-channel recording allows for both an ipsilateral and a contralateral ABR to be recorded simultaneously. There are several advantages to simultaneously obtaining both an ipsilateral and a contralateral recording. First, the contralateral recording can assist in locating wave I. Typically wave I is present in the ipsilateral tracing and is absent or quite reduced in amplitude during the contralateral recording. However, wave I' is typically present in the contralateral recording and can assist in determining the exact location of wave I in the ipsilateral recording. Second, the contralateral recording

typically presents with a clear separation of waves IV and V, while an ipsilateral recording presents with fused waves IV and V (Picton, 2011).

When the stimulus is delivered to the right ear, the noninverting electrode is placed on Cz, two inverting electrodes are placed on A2 (right earlobe) and A1 (left earlobe), and the ground electrode is placed on the forehead. Electrodes Cz-A2 would be designated to channel A in the electrode box, while electrodes Cz-A1 would be designated to channel B. Channel A would be denoted as the ipsilateral channel and channel B would be denoted as the contralateral channel. The response from both of these recording channels would be recorded simultaneously. For the purposes of the proposed study, we will be acquiring a two-channel (ipsilateral and contralateral) recording of the click-evoked ABR using the electrode montage described above.

Analog EEG Bandpass Filtering.

One important decision made by audiologists when recording ABRs is where to set the high pass (HP) and low pass (LP) cutoff frequencies for the analog bandpass filter. The answer to this question is determined based on the spectral energy present in the response (Suzuki, Sakabe, & Miyashita, 1982). The aim of the bandpass filter is to capture the energy present in the response and not allow contributions to the response from frequencies outside this frequency region.

An ABR is typically acquired using an analog bandpass filter. The bandpass filter includes both a HP cutoff frequency and a LP cutoff frequency (Hood, 1998; Janssen, Benignus, Grimes, & Dyer, 1986). A HP filter restricts low-frequency energy from contributing to the recording, and a LP filter prevents high-frequency information

contributions (Hood, 1998). For example, an analog bandpass filter setting of 100 Hz to 3000 Hz would prevent any energy below 100 Hz and above 3000 Hz from contributing to the waveform. However, energy of the response between 100 Hz and 3000 Hz would be passed through.

In 1982 Suzuki, Sakabe, and Miyashita conducted a study to determine what main frequencies of energy were present in the ABR. These researchers did this by conducting a power spectral analyses on the ABRs of three normal-hearing adults using Fast Fourier Transform (FFT) analysis. The ABRs were recorded to 1000, 2000, and 4000 Hz tone burst stimuli presented at an intensity of 80 dB SPL. ABRs were also recorded to 500, 1000, and 2000 Hz tone bursts at a lower stimulus intensity (40 dB SPL) to see if this spectrum of energy present in the response was dependent on stimulus intensity. Suzuki and colleagues reported that the ABRs recorded at the higher stimulus intensities had three main peaks of energy. These three peaks occurred between 50-150, 500-600, and 900-1100 Hz and are labeled peaks A, B, and C in figure 11 below. The researchers also reported that the two peaks containing the higher stimulus frequencies (i.e., 500-600 and 900-1100 Hz) substantially decreased in amplitude or were completely absent when stimulus intensity was decreased to 40 dB nHL. Since the spectral energy ABR recorded to high-intensity stimuli occurs approximately between 100 Hz and 1200 Hz, it is important to select an analog bandpass filter that will not exclude any of the energy within this range. Therefore, click evoked ABRs are typically recorded using an analog bandpass filter from 100 Hz to 3000 Hz.

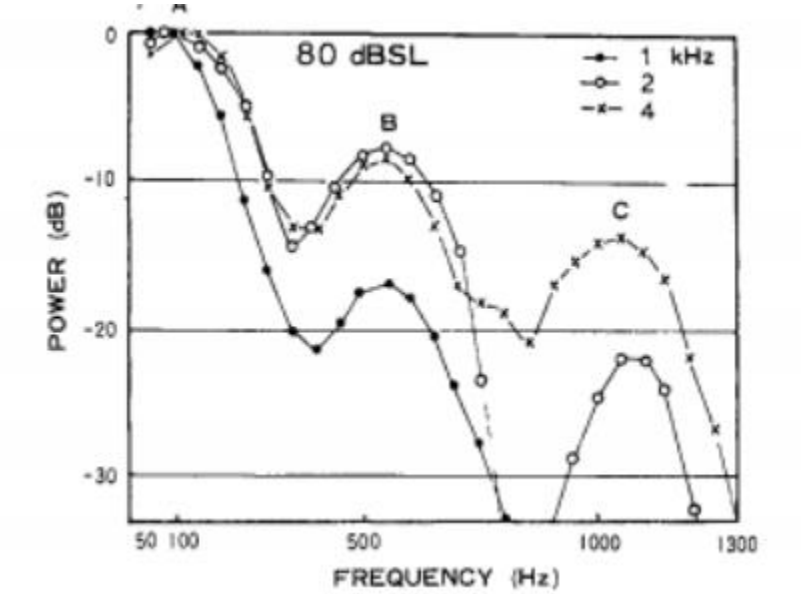

Figure 11. Spectrograms of ABRs recorded with 1000, 2000, and 4000 Hz tone burst stimuli with an intensity of 80 dB SPL (Suzuki et al., 1982).

According to Elberling (1979), the majority of the spectral energy present in the ABR is located below 250 Hz. He determined this by running a frequency analysis on recorded templates of the ABR. Figure 12 represents the frequency analysis of an ABR recorded with a 105 dB SPL click in an individual with normal hearing. The Y axis represents amplitude of the energy in the response ranging from -40 dB SPL (lowest) to 0 dB SPL (highest). The X axis represents the frequencies at which the energy is present, ranging from 31 Hz to 2000 Hz. As depicted in the figure, the most energy present in the ABR occurs below 250 Hz, with some energy present around 500 Hz and 1000 Hz. Elberling's finding is in good agreement with the results of Suzuki et al (1982).

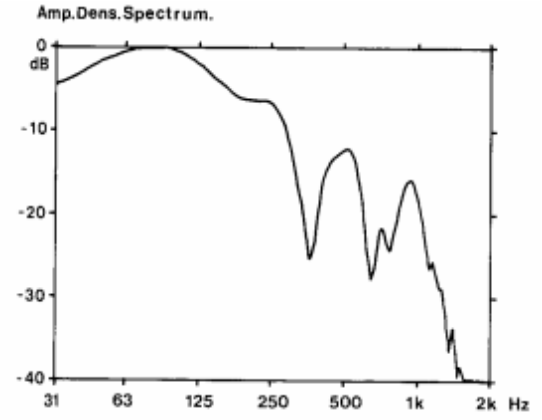

Figure 12. Spectral analysis of an ABR recorded with a 105 dB SPL click. Along the X-axis is amplitude of the energy present in the signal and along the Y-axis is frequency of the energy. Most of the energy is present below 250 Hz (Elberling, 1979).

Another important consideration regarding analog filtering for the ABR is the slope of the HP and LP filters. The slope of a filter refers to the level of steepness of the cut-off frequency. Elton, Scherg, and Von Cramon (1984) investigated the effects of filter slope on the ABR by manipulating the HP filter slope. These investigators recorded ABRs in 20 normal-hearing adults and increased the filter slope of a 150 Hz HP filter from 6 dB/octave to 24 dB/octave in 6 dB/octave steps. They found that filter slopes greater than 12 dB/octave produced notable distortion in the ABR waveform. Specifically, the researchers observed reduction in amplitude for waves I, III, and V, as well as changes in the wave IV-V complex. Therefore, a filter slope no greater than 12 dB/oct should be used when recording ABRs.

In summary, in order to capture energy pertaining to the ABR, an analog bandpass filter ranging from 100 Hz to 3000 Hz with a 12 dB/oct slope will be used for the proposed study.

Number of Sweeps.

The number of sweeps completed in the recording of an ABR, also known as the number of trials, has a direct impact on the level of EEG noise present in the response. Auditory evoked potentials, such as the ABR, are recorded using signal averaging techniques. The principles of signal averaging are based on the assumption that the response to the signal (i.e., the ABR) is stationary in time or "time-locked to the onset of the stimulus" and the background noise is random (Picton et al., 1983). Thus, the aim of signal averaging is to enhance the amplitude of the desired neural signal relative to the amplitude of the ongoing background EEG and myogenic noise. The number of ABR sweeps that are recorded in a session contribute to the signal averaging process. Signal averaging techniques allow for the amplitude of random, non-stationary background noise to be reduced by an amount equal to the square root of the number of sweeps recorded (Picton, 1981). Hence, recording more sweeps allows for the desired neural signal to be more prominent against background noise (Hood, 1998; Picton et al., 1981). This comparison of the signal to the background noise is known as the "signal-to-noise ratio" (SNR) (Picton et al., 1983).

According to Picton et al., (1983), the desired SNR for an otoneurologic click-evoked ABR is 2:1. These researchers reported that 1600 sweeps were necessary to obtain an SNR of 2:1. Another procedure that helps to eliminate background noise and ensure an appropriate SNR exists is replicating the waveform. Undergoing the averaging process a second time allows for comparison between the first recording and the second recording. If there are differences in amplitude, it is possible that at least one of the waveforms was contaminated by EEG background noise (Picton et al., 1983). Two replicable waveforms

can be summed so that the total number of sweeps is doubled and, therefore, background noise is further reduced for a more favorable SNR. For the purposes of the proposed study, at least two replications of 1,024 sweeps each will be recorded, allowing for a total of 2,048 sweeps.

Artifact Rejection.

Manipulating the artifact rejection criterion level is another method of decreasing the effects of background noise on the ABR. During recording, sweeps may occur where excessive levels of background noise are present. As a result, the level of background noise skews the ongoing averaging so that the ABR is less prominent and more difficult to identify (Don & Elberling, 1994). Clinicians can keep excessive noise from contributing to the response by setting an artifact rejection criteria that discards any sweeps containing voltage values greater than the signal of interest (Hood, 1998; Katz, 2009). In order for artifact rejection to be effective, an appropriate artifact rejection criteria must be selected. The more stringent the rejection criteria, the more sweeps that are omitted (Don & Elberling, 1994). A high level of rejected sweeps leads to a higher number needed for overall sweeps, which causes test time to increase (Don & Elberling, 1994). Since voltage of click-evoked ABRs range between 0.1 µV to 0.5 µV (Hood, 1998), an artifact rejection criterion of ± 25 µV will be used for the proposed study. This level is strict enough so that excessive noise clearly unrelated to the response can be discarded, but not so strict that an excessive number of sweeps would be rejected. Also this artifact rejection criteria has been successfully used in many ABR studies and is routinely used in clinical practice (Hood, 1998).

Differential Amplification and Common Mode Rejection.

Due to the ABR having a small amplitude (around 0.5 μV), it is important that the response be amplified so that it is visually large enough for interpretation (Hood, 1998). A certain amount of gain must be applied to the response so that it can be large enough for interpretation. This is accomplished through the use of a differential amplifier. Typically, a gain of 100,000 times is applied to the ABR.

An important aspect of the differential amplifier is the common mode rejection process. Common mode rejection works by detecting noise that is common to two electrodes placed on the scalp and subtracting the noise so that the desired response can be amplified. For example, when one electrode is placed on Cz (non-inverting) and the other on A1 (inverting), the desired response transmitted to each electrode is different at each site. However, any noise recorded by the electrodes should be identical for both recording sites. After the subtraction of noise common to both electrodes takes place, the remaining voltage (i.e. the desired auditory evoked response) is amplified (Hood, 1998).

Length of the Post-stimulus Analysis Window.

The length of the post-stimulus analysis window, in milliseconds, is an important factor to consider when recording an ABR. In response to a high-intensity click stimulus, a traveling wave is propagated along the basilar membrane of the cochlea within 2 to 5 ms following stimulus onset (Picton et al., 1981). As a result, the ABR can be observed within 5 to 6 ms after presenting a high-intensity click stimulus, and between 8 and 9 ms in response to a low-intensity click stimulus. (Hood, 1998). It is important that the length of the analysis window encompasses the time period when the response occurs. Therefore,

the length of the post-stimulus analysis window is typically set from 0 ms to 10 -12 ms (Hood, 1998). For the proposed study, a post-stimulus analysis window of 16 ms will be employed, since the Biologic AEP system does not include the option of a 12 ms post-stimulus analysis window length.

Effect of Various Subject-Related Factors on the ABR

Various subject factors can potentially have an impact on ABR recordings. The three primary subject factors that may affect an auditory evoked potential include the subject's state (natural sleep and drug-induced sleep), subject's age, and the subject's gender. These subject parameters and their possible influence on the ABR are discussed below.

Subject-State

Natural sleep.

Natural sleep is a subject factor that has been shown not to have a substantial influence on the ABR (Osterhammel, Shallop, & Terkildsen, 1985; Campbell & Batroli, 1986). Osterhammel, Shallop and Terkildsen (1985) investigated the effects of the four stages of sleep on the ABR, with stage 1 being the lightest and stage 4 being the deepest stage of sleep. ABRs from one subject during an awake state and during stages 1, 2, 3, and 4 are provided in figure 13 below. This subject's ABRs to a 60 dB nHL click stimulus were continuously recorded overnight. The subject's stages of sleep were determined by monitoring their EEG activity throughout the night. As can be seen in the figure, the subject's ABR was highly replicable throughout every stage of sleep.

Latencies for waves I, III, and V were nearly identical across all five conditions. These researchers reported no significant changes in the latencies or amplitudes of the ABR peaks across all four stages of sleep. Furthermore, they stated that ABR latencies recorded during sleep are similar to those recorded during an awake state.

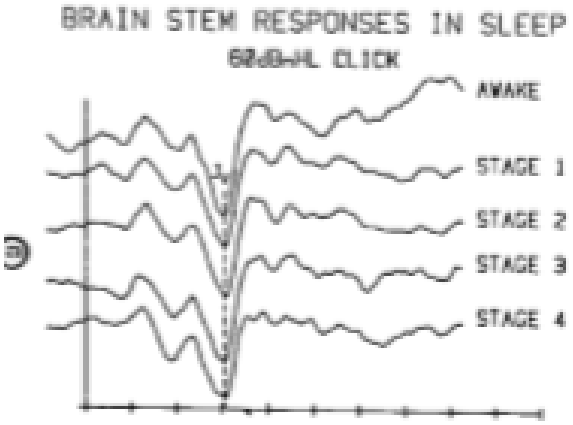

Figure 13. One subject's ABRs recorded to a 60 dB nHL click stimulus during an awake stage and four stages of natural sleep. Latencies for waves I, III, and V are similar across all stages (Osterhammel, Shallop & Terkildsen, 1985).

Similarly, Campbell and Batroli (1986) examined the effects of natural sleep on the ABR. These researchers recorded ABRs in nine female subjects over the course of one night during natural sleep. A 70 dB nHL click stimulus was used to elicit ABRs at rates of either 11, 41, or 81/sec. All three click rates were used to record ABRs during an awake-state and during stages 2, 4 and REM. Campbell and Batroli reported that the latencies and overall morphology of the ABR remained the same throughout all sleep

stages. The responses recorded during the various stages of sleep were nearly identical to those recorded during the awake stage. This was true for all three click rate conditions. Therefore, these researchers concluded that natural sleep had little to no effect on latencies of the ABR.

Collectively, the evidence from these two studies suggests that reliable ABRs can be recorded regardless of a participant's state of arousal.

Drug-induced sleep.

Drug-induced sleep has also been shown not to have a noticeable impact on ABR recordings. At times, energetic patients (i.e., children) who demonstrate too much activity for a reliable ABR require sedation (Picton, 2011). Therefore, it is important to verify that drug-induced sleep does not have an impact on ABR measurements. Sohmer, Gafni, and Chisin (1978) reported that sedated ABRs in children are nearly identical to ABRs recorded while children are awake. These researchers recorded ABRs from six children between the ages of 5 and 10 years old who were undergoing dental surgery. ABRs were recorded during two conditions: when the children were awake and when the children were sedated in preparation for surgery. A 75 dB nHL click stimulus presented at a rate of 10/sec was used to record the ABR. Absolute latencies, wave I-V IPL, and peak-to-peak amplitudes for all five peaks were measured. Sohmer et al. reported that there were no significant differences in the latencies or amplitude values between the awake condition and the sedated condition. Table 1 provides a summary of the mean latencies and amplitudes recorded for both the awake and sedated test conditions.

Table 1.

Means and Standard Devations of ABR Latencies and Amplitudes between Awake and Asleep Conditions (Sohmer, Gafni, & Chisin, 1978).

		Latency, msec						Amplitude μV				
		W_1	W_2	W_3	W_4	W_5	W_4-W_1	W_1	W_2	W_3	W_4	W_5
Awake, 11 ears	$\bar{X}$	1.336	2.500	3.509	5.351	6.200	4.663	0.854	0.609	0.763	0.818	0.527
	SD	0.112	0.148	0.138	0.292	2.070	0.287	0.207	0.170	0.112	0.166	0.127
Sedated sleep, 11 ears	$\bar{X}$	1.281	2.454	3.472	5.290	6.845	4.572	0.827	0.518	0.718	0.854	0.536
	SD	0.098	0.121	0.119	0.251	0.169	0.317	0.261	0.214	0.227	0.207	0.081

According to the literature, accurate ABRs can be attained regardless of a patient's state of arousal (Campbell & Batroli, 1986; Sohmer, Gafni & Chisin, 1978). This is true for both natural sleep and for drug-induced sleep. Although ABRs recorded during an awake state have been reported to be similar to those recorded during sleep, it is recommended that clinicians instruct their patients to sleep during ABR testing. This is because the patient's EEG activity is drastically reduced during sleep, making muscle activity less likely (Picton, 2011). Therefore, in the proposed study we will be instructing participants to try and sleep during the recording of their ABR. to interfere with the ABR.

Age-Related Changes in the ABR

Infancy.

Amplitude and latencies of the ABR can differ depending on the age of the subject. This is especially true during infancy. A healthy, normal-hearing newborn will have an ABR with notably smaller amplitudes and longer latencies than an adult's

response (Picton, 2011). Wave I and wave V of infant ABRs do not reach adult latency values until the ages of 6 months and 2 years, respectively. In response to a 70 dB nHL click stimulus, a newborn's I-V IPL should be about 5 ms, while an adults I-V IPL is a full millisecond shorter. Additionally, the absolute latency of wave V for a newborn is approximately 7 ms, while an adult's wave V absolute latency measures around 5.7 ms (Picton, 2011).

Starr et al. (1977) investigated the effect of age on infants' ABRs by recording click-evoked ABRs in 42 infants between the ages of 26 and 44 weeks. These researchers recorded the ABRs to click stimuli presented at 65 dB SL using a click rate of 10/sec. The responses were filtered with a bandpass filter setting of 100-3000 Hz. These researchers reported that wave V absolute latency decreased from 9.9 ms to 6.9 ms from 26 weeks of age to 40 weeks of age. They also reported that IPL I-V decreased from 7.2 ms at 26 weeks to 5.2 ms at 40 weeks. Therefore, these findings suggest that the ABR undergoes a period of maturation during the first 40 weeks of life, and that ABRs from healthy infants present differently than ABRs from normal-hearing adults. As we will only be testing young adults for the proposed study, this finding will not have an impact on the normative data collected.

Effects of Age on the ABR.

Old age is another subject factor that can influence ABR outcomes. Latencies, in particular, have been observed to increase slightly and be more variable as a function of old age (Rowe, 1978; Picton, 2011). Rowe (1978) recorded ABRs in a group of 25 young adults between the ages of 17-33 years and in a group of 25 older adults between the ages of 51-74 years in order to assess the effects of older age on ABR response measurements.

The ABRs were recorded under three different conditions: (1) a 60 dB SL click presented at a rate of 10/sec, (2) a 60 dB SL click presented at a rate of 30/sec, and (3) a 30 dB SL click presented at a rate of 30/sec. This test paradigm allowed the researchers to observe the effects of old age on the ABR in response to rate changes and intensity changes. Rowe reported that the absolute latencies of ABR peaks I-VII were delayed in the older subjects for all three test conditions. The age-related latency differences were even more pronounced at the lower versus higher stimulus intensities. Table 2 below summarizes the average absolute latencies for the young and old groups across all three recording conditions.

Table 2.

ABR Absolute Latencies from Three Different Recording Conditions for Young and Old Subjects (Rowe, 1978).

Wave Peak Latencies for all stimulus conditions, right and left ears combined. Times given in milliseconds. S.D. = standard deviation.

Waves	60 dB-10/sec		60 dB-30/sec		30 dB-30/sec	
	Mean (S.D.)	Number	Mean (S.D.)	Number	Mean (S.D.)	Number
Young subjects						
1	1.87 (0.18)	47	1.96 (0.21)	47	3.16 (0.36)	40
2	2.88 (0.20)	38	2.98 (0.28)	37	4.01 (0.36)	21
3	3.83 (0.20)	50	4.01 (0.18)	50	5.18 (0.31)	46
4	5.06 (0.23)	43	5.19 (0.28)	38	6.36 (0.36)	18
5	5.82 (0.25)	50	6.01 (0.25)	50	7.13 (0.33)	49
6	7.37 (0.46)	50	7.70 (0.45)	46	8.95 (0.40)	36
7	9.05 (0.47)	48	9.24 (0.42)	38	—	—
Old subjects						
1	2.17 (0.27)	50	2.16 (0.31)	50	4.21 (0.61)	37
2	3.36 (0.31)	41	3.28 (0.33)	43	4.96 (0.62)	17
3	4.35 (0.26)	50	4.45 (0.35)	50	6.28 (0.51)	38
4	5.43 (0.34)	24	5.54 (0.35)	30	7.35 (0.41)	22
5	6.16 (0.26)	49	6.37 (0.27)	50	8.21 (0.47)	48
6	7.95 (0.38)	50	8.18 (0.42)	48	9.50 (0.44)	13
7	9.30 (0.51)	41	9.38 (0.48)	33	—	—

Note. Older subjects have longer latencies than younger subjects, regardless of stimulus intensity or click rate.

Although age effects will not be a factor, clinicians referring to the norms gathered in the proposed study should consider age effects if they are testing infants or older adults.

Effects of Gender on the ABR

Gender is another subject factor that can impact the ABR. In general, ABRs in females present with shorter latencies and larger amplitudes than males (Hood, 1998; Picton, 2011). According to Kjaer (1979), females have significantly shorter wave III and wave V latencies than males, and significantly larger amplitudes for all waves of the ABR. This researcher recorded ABRs in 21 female and 19 male subjects between the ages of 13 and 48 years with normal hearing. The ABRs were recorded to a 75 dB nHL click stimulus presented at a rate of 5/sec. ABR peaks beyond wave II were noted as significantly longer in females than in males. The mean absolute latency for wave III was 3.63 ms in females and 3.71 ms in males. For wave V, the mean absolute latency was 5.54 ms in females and 5.75 in males. The other major gender difference in the ABR was peak-to-peak amplitude values. All five peaks were reported to have significantly larger amplitudes in females than in males. For example, the females had a mean wave V amplitude of 0.60 µV, while the males only had a mean wave V amplitude of 0.48 µV.

Jerger and Hall (1980) examined the effects of gender on wave V of the ABR. Their sample size included 182 male and 137 female subjects between the ages of 20 and 79 years. The ABRs were recorded to click stimuli presented at intensities of 70 dB HL and 90 dB HL. These researchers reported that, on average, wave V absolute latencies for males were approximately 0.14 ms longer than for females. Regarding wave V amplitude, female measurements were consistently larger than male amplitudes, with

differences ranging between 0.080 μV and 0.120 μV. Wave V amplitude was larger in females than in males by approximately 25%.

Various rationales have been suggested to explain why females have shorter absolute latencies and larger wave V amplitudes than males. One of the rationales includes difference in head sizes between men and women. Dempsey, Censoprano, and Mazor (1986) investigated this theory by matching men and women for head size and comparing latencies and amplitudes of ABR wave V. They found that when men and women were matched for the physical diameter of their head, women still presented with shorter wave V latencies and larger amplitudes for wave V-V' in comparison to men. They also reported that the absolute latency of wave V increased with increasing head size regardless of gender. Therefore, Dempsey et al. (1986) concluded that head size cannot explain the gender differences seen in the response measurements of ABR wave V.

Body temperature has also been suggested as a rationale for differences between male and female ABR measurements (Hall, 2007). This is because, on average, men have a higher core temperature than women by approximately 0.3 degrees Celsius. However, this small difference in temperature between the two genders is not great enough to have an impact on ABR measurements. Conditions such as hypo- and hyperthermia, where body temperature is either abnormally low or abnormally high, are more likely to affect ABR latency and amplitudes. When recording an ABR, it is only pertinent that body temperature be monitored and documented in individuals who might be at risk for either of these conditions (Hall, 2007).

More recently, Don, Ponton, Eggermont, and Masuda (1993) aimed to evaluate the reasons why ABR response measurements differ between the two sexes. These researchers recorded high-pass noise/derived band ABR responses in 17 female and 14 male normal-hearing subjects between the ages of 18 and 38 years. Rarefaction click stimuli were presented at intensities of 93, 83, 73, 63, 43, and 38 dB peak equivalent SPL. Two stimulus presentation conditions were implemented for each intensity level: a rarefaction click stimulus (1) in the absence of masking noise and (2) in the presence of pink noise masking with high-pass filters of 8000, 4000, 2000, 1000, and 500 Hz presented to the same ear. The pink noise masking allowed for certain frequency regions of the cochlea to be excluded from the measured response. Derived band ABRs were measured by sequential subtraction of the responses with each decrease in high-pass filter of the masking noise. This resulted in derived band ABRs elicited from regions of the cochlea with center frequencies (CF) of 11,300, 5700, 2800, 1400, and 700 Hz.

Don et al. (1993) reported that latencies for waves I and V were shorter in females than in males for all derived narrowband responses at every intensity level. For example, for the 5700 Hz derived narrowband response elicited with a click intensity of 83 dB p.e. SPL, females had wave I and wave V mean absolute latencies that were 0.28 ms and 0.34 ms shorter than the male mean absolute latencies, respectively. According to this finding, it is evident that females have shorter cochlear travel times for an auditory stimulus than do males. Shorter cochlear travel times in females result in the stimulus arriving at wave V generators more quickly, as well as better neural synchrony of the eighth nerve. Don et al. concluded that the shorter cochlear travel times and the better neural synchrony of the

VIIIth nerve result in earlier latencies and larger amplitudes for wave V in females than in males.

In summary, female subjects have repeatedly been shown to have shorter ABR latencies and larger amplitudes than males. This is particularly true for the latency and amplitude of wave V (Don et al., 1993). To account for these gender effects on the ABR, there will be an attempt made to recruit an equal number of male and female participants for the proposed study.

Sensitivity and Specificity of the ABR

As discussed previously, the main purpose of the otoneurologic ABR is to detect the presence of tumors on the eighth nerve. Sensitivity of the ABR is known as the rate at which eighth-nerve tumors are correctly identified (Don & Kwong, 2009). Conversely, specificity is the rate at which non-tumor cases are correctly identified (Bauch, Rose, and Harner, 1982). Sensitivity and specificity rates of the ABR will be discussed in the following section.

For the ABR to be considered clinically valuable, it must have an adequate rate of sensitivity. Reports in the literature on the sensitivity of the ABR have been variable, largely because of differences in tumor size (Don & Kwong, 2009). Smaller-sized tumors can often go undetected with standard ABR response measurements (Don & Kwong, 2009; Godey et al., 1998). Godey et al. (1998) were interested in determining how sensitive the ABR was at detecting intracanalicular and extracanalicular eighth nerve tumors. These researchers retrospectively reviewed the files of 89 patients who had undergone acoustic neuroma surgery. All subjects had ABR testing as well as MRI evaluations which confirmed the presence of an acoustic neuroma. ABRs were recorded

with a click stimulus presented at intensities of 80, 90, and 100 dB nHL. The click rate for these recording was 20/sec. There were four different criteria used to judge an ABR as abnormal 1) an IPL of waves I-III > 2.5 ms, 2) an IPL of waves I-V > 4.4 ms, 3) an ILD of wave V > 0.2 ms, 4) and an interaural difference of IPL I-V > 0.2 ms. Of the 89 acoustic neuroma patients, 7 had normal ABRs and 82 had abnormal ABRs. This resulted in a 92% rate of sensitivity for the ABR. The researchers reported that patients with tumors 18 mm and larger always had abnormal ABRs. The mean size of tumors for patients with normal ABRs was 15 mm. This finding led the researchers to conclude that the ABR was more clinically valuable in detecting larger acoustic neuromas rather than smaller acoustic neuromas.

In a similar study, Wilson et al. (1992) examined the sensitivity of the ABR in detecting small tumors versus larger tumors. These researchers performed a retrospective examination of 40 patients with acoustic neuromas confirmed by MRI. Click-evoked ABRs were recorded at 80 dB nHL using rates of 13.3 and 53.3 per second. ABRs were considered abnormal based on the following four criteria: 1) an ILD of wave V $\geq$ 0.4 ms, 2) an interaural difference of IPL I-V $\geq$ 0.4 ms, 3) an IPL of waves I-V $\geq$ 4.4 ms, and 4) poor wave morphology in the presence of normal hearing. Of the 40 patients, six presented with normal ABRs, despite having confirmed acoustic neuromas. Tumor size in these six patients ranged from 3 mm to 13 mm. These researchers concluded that ABRs are less sensitive for smaller sized tumors, and that MRI should be used to detect tumors smaller than roughly 1 cm.

Although standard ABR recording techniques have been reported to be less sensitive for detecting tumors < 1 cm, the stacked ABR is an alternative method that has

been shown to be accurate in detecting small acoustic neuromas (Don et al., 1997). Normal ABR response measurements can occur in individuals with small acoustic neuromas because these measurements are being elicited by cochlear frequency regions in which the small tumor does not have an impact (i.e., high-frequency regions). To address this issue, the stacked ABR utilizes high-pass filtered noise presented in the same ear as the click stimulus. This high-pass noise is used to mask certain frequency regions of the cochlea to prevent them from contributing to the ABR. For example, while a click stimulus is being presented to the test ear and an 8000 Hz high-pass noise (HPN) is presented simultaneously to that same ear, the frequency region below 8000 Hz is allowed to contribute to the ABR, while the frequency region above 8000 Hz is masked out. From here, ABRs are successively elicited with 4000 Hz, 2000 Hz, 1000 Hz, and 500 Hz high-pass filters. Each decrease in high-pass filter setting allows for assessment of contributions to the ABR from lower frequency regions of the cochlea. Specific narrowband contributions to the ABR can then be derived by subtracting one response in HPN from the response recorded in HPN from the next highest HPN cutoff frequency. For example, the response recorded in the presence of 4000 Hz HPN is subtracted from the response recorded in the presence of 8000 Hz HPN. This subtraction procedures results in a derived band waveform which is representative of the 4000-8000 Hz narrowband region of the cochlea (Don et al., 1997). In this technique, after the series of one-octave wide derived responses are calculated, they are adjusted such that the latency of wave V is temporally aligned to occur at the same point in each of the five derived bands. Once the temporal alignment of wave V latency has occurred, the 5 derived responses are summed and the total wave V-V' amplitude for the stacked ABR is

determined. A reduction in the wave V-V' amplitude of the stacked ABR re normative data suggests that a tumor is impacting a noteworthy number of fibers responsible for contributing to the response.

Don et al. (1997) assessed the reliability of the stacked ABR in detecting acoustic neuromas smaller than 1 cm by recording standard click-evoked ABRs and stacked ABRs in 24 subjects and 25 ears with confirmed acoustic neuromas, the largest being 2.2 cm. A click with a 93 dB peak-to-peak equivalent SPL (using a 1000 Hz tone for reference) was used to elicit the ABRs. Recording conditions included an unmasked condition, and clicks presented with simultaneous high-pass noise presented ipsilaterally with cutoff frequencies of 8000, 4000, 2000, 1000, and 500 Hz. For the unmasked condition, abnormal ABR criteria included prolonged wave I-V IPL (>4.2 ms). Prolonged wave V ILD (>0.2 ms) was also considered for tumor patients who did not have NF 2 (bilateral tumors) and did not have significant asymmetrical hearing affecting the nontumor ear. Out of the 25 subjects with confirmed tumors, 5 subjects with tumors ≥ 1 cm presented with normal nonmasked ABRs. However, all 25 subjects had abnormal wave V amplitudes when tested with the stacked ABR. Therefore, these researchers concluded that the stacked ABR was a more sensitive measure in detecting small tumors than the nonmasked click-evoked ABR (Don et al., 1997).

In summary, findings reported in the literature indicate that the ABR is highly sensitive at detecting acoustic neuromas which are greater than 1 cm with an average sensitivity rate of about 95% and specificity of about 25% (Godey et al., 1998; Gstoettner, 1992; Wilson et al., 1992). However, small acoustic neuromas less than 1 cm can go undetected by the ABR. This is because smaller tumors are not substantial enough

in size to cause stretching of, compression of, or lack of blood supply to the eighth nerve, which are all causes of dyssynchrony of the ABR (Wilson et al., 1992). Although the MRI is considered the gold standard for detecting acoustic neuromas down to 3 mm, the ABR is still valuable in that it is much less costly and has a high sensitivity rate of about 95% (Don & Kwong, 2009).

Calibration of AEP Equipment

In order to obtain accurate responses, it is imperative that the ABR equipment be calibrated. There are two main techniques used to calibrate the intensity of the click stimulus, both of which will be described below.

The first calibration method is called the peak-hold measure. This is considered to be the more precise calibration technique of the two (Beattie & Rochverger, 2001). The equipment needed to perform this method includes a 2-cc coupler and a sensitive sound level meter (SLM) with a peak-hold feature. The SLM must be capable of recording brief stimuli, such as a 100 microsecond (μsec) click. To perform this technique, the transducer of the ABR equipment must be attached to the 2-cc coupler on the SLM. A click stimulus is then played through the ER3A insert earphone transducer. An SLM with a peak-hold feature will recognize and capture the peak energy present in the stimulus, which is also known as the loudest, instantaneous portion of the stimulus (Katz et al., 2009). The audiologist then reads this peak SPL level from the dial on the SLM.

The second calibration method is known as the peak-to-peak equivalent sound pressure level (ppe SPL). To perform this technique, a 2-cc coupler, an SLM, and an oscilloscope are needed (Beattie & Rochverger, 2001; Katz et al., 2009). A stimulus is

played through the ER3A insert earphone transducer of the ABR equipment, which is attached to a 2-cc coupler on the SLM. An output cable is then routed from the SLM to the oscilloscope, where the magnitude of the output is displayed. The magnitude is adjusted so that roughly two boxes of the oscilloscope graph, or 10 µV, is occupied by the output sine wave. An identical procedure is done next, using a continuous 1000 Hz pure tone stimulus from an audiometer attached to the SLM. The same transducer and same settings on the SLM are employed. The 1000 Hz pure tone sine wave from the audiometer is then adjusted in intensity to match the peak-to-peak voltage of the ABR stimulus that had been previously adjusted on the oscilloscope. This type of procedure is done because a SLM without a peak hold feature is unable to capture the brief energy present in the 100 µs click stimulus and provide an accurate output reading. A 1000 Hz pure tone, however, is a continuous stimulus that the SLM is capable of recognizing. The measurement on the SLM is viewed to confirm the anticipated output in dB SPL (Beattie & Rochverger, 2001; Katz et al., 2009).

It is important to identify the particular method being used for calibration of the stimuli when explaining how the equipment is calibrated. This is because there is a slight difference in value between a peak hold measure and a peak-to-peak equivalent sound pressure measure. The peak hold method allows for the energy at the precise peak of the signal to be captured on the SLM. However, the peak-to-peak equivalent sound pressure method captures a less specific 3 dB down point from the peak. Therefore, there is a 3 dB difference between the two calibration procedures (Katz et al., 2009). For example, if the peak SPL measurement is 93 dB SPL, the peak-to-peak equivalent (ppe SPL) measurement for that same stimulus would be 90 dB ppe SPL.

The AEP equipment was also calibrated for linearity across several different stimulus intensities. Linearity of the equipment refers to how accurately the attenuator increases and decreases the intensity of the stimulus. For example, when the intensity of the stimulus is changed from 80 to 70 dB nHL, it is expected that a 10 dB decrease in the SPL measurement will be seen. The linearity of the Biologic AEP equipment was checked for the following 10 dB steps: (1) 90 to 80 dB nHL and (2) 80 to 70 dB nHL. This will be observed using the same instrumentation and set up that was used in the peak-to-peak equivalent technique.

Finally, the click stimulus was calibrated for polarity. To perform this type of calibration, both a rarefaction click stimulus and a condensation click stimulus were played through an ER-3A insert earphone attached directly into the oscilloscope. The resulting square waves were visually observed to determine that they are each representative of the correct polarity. It is expected that the condensation click will have an initial positive peak followed by a negative peak. The opposite pattern is expected for the rarefaction click (i.e., an initial negative peak followed by a positive peak).

Statement of Purpose

The purpose of the present study was to collect normative data for the ABR on the Bio-logic AEP system at the Towson University Hearing and Balance Center. Norms were based on a group of normal-hearing young adults with no history of otologic and/or neurologic pathology. This was to ensure that ABR measurements contributing to the normative data are representative of typically-developed, intact auditory pathways. The response measurements that were collected include: (1) absolute latencies of waves I, III

and V; (2) IPLs of waves I-III, III-V, and I-V; (3) ILD for waves V and I-V; (4) rate differences between 19.1 and 61.1/sec recordings, and (4) wave V/I amplitude ratios. Additionally, ANSD was ruled out by comparing responses to rarefaction and a condensation polarity click stimuli. This normative data will be used as a reference for student clinicians and clinical supervisors performing otoneurologic ABRs at the Towson University Hearing and Balance Center.

CHAPTER 3: MATERIALS AND METHODS

Subjects

Participants in this study included 20 normal-hearing individuals (10 male and 10 female) between the ages of 20 and 26 years. The criteria for normal hearing were as follows: (1) bilateral pure tone behavioral thresholds ≤ 15 dB HL from frequencies 250 Hz-8000 Hz for air conduction, (2) normal tympanograms indicating healthy middle ear status, which includes a peak pressure that falls within the range of -100 to 50 daPa (Katz, 2009), a static compliance between 0.2-1.4 ml (Margolis & Heller, 1987), and ear canal volumes ranging between 0.63-1.46 ml (Margolis & Heller, 1987), (3) contralateral acoustic reflexes at 500, 1000, and 2000 Hz that fall within the 90th percentile data in each ear (Gelfand, Schwander, & Silman, 1990) and (4) no self-reported history of otologic and/or or neurologic problems. Subjects were recruited by general invitation (i.e., social media announcement and email invitation). The proposed study was approved by the Institutional Review Board at Towson University.

Equipment and Procedures

Audiologic Equipment

Equipment used for audiologic testing included an otoscope for visual examination of the outer ear, a GSI-61 audiometer for pure tone behavioral testing, and a GSI Tympstar immitance bridge for tyamponmetric measures and ARTs.

Auditory Evoked Potentials Equipment

ABRs were recorded and analyzed using the Bio-logic AEP system, four electrodes, and two ER-3A insert earphones. The stimulus and recording parameters that were used for this portion of the study are described below.

Procedures

Both audiologic and electrophysiologic portions of the test took place in one session that lasted for approximately two to three hours. All testing took take place at the Towson University Hearing and Balance Center. Prior to testing, a short case history questionnaire on the participant's otologic and neurologic health was administered. Then, otoscopy was performed, followed by tympanometry. Next, contralateral ARTs for both ears were recorded. Finally, air conduction behavioral pure tone thresholds were obtained for both ears from frequencies 250 – 8000 Hz. Any participants who failed to meet the specified selection criteria were excluded from participating in the remainder of the study.

Pure Tone Behavioral Procedures.

Pure tone behavioral air conduction testing was administered using a GSI-61 audiometer and ER-3A insert earphone transducers. The Modified Hughson-Westlake procedure was used to determine thresholds to pulsated pure tone stimuli. Participants were asked to sit in a chair facing toward the person presenting the pure tone stimuli. Participants were handed a button and instructed to press the button every time they heard a tone, even if the tone sounded faint. They were informed that the purpose of the hearing test was to determine the softest level of tones they could hear. Participants were informed that first they would be tested in the right ear, followed by the left ear.

Otoneurologic ABR Procedures.

The electrode montage was arranged to allow for recording of a two-channel ABR (ipsilateral and contralateral). The noninverting electrode was placed on Cz, the two inverting electrodes were placed on sites A1 and A2, and the ground electrode was placed on the forehead. Electrode impedance values for each individual electrode were5 kOhms or below with a difference of less than 2 kOhm between electrodes. An analog bandpass filter-setting of 100-3000 Hz with a slope of 12 dB/oct was employed. The artifact rejection criteria was set to $\pm$ 25 µV and the length of the post-stimulus analysis window was 0 – 16 ms. At least two replications of 1024 sweeps each were recorded for every test condition, amounting to a total of 2048 sweeps per test condition.

Oto-neurologic ABRs were recorded using a Bio-logic AEP system with two ER-3A insert earphones to deliver the stimuli. The order of which ear to be tested first was

randomized across subjects. Participants were asked to recline in a comfortable chair and encouraged to sleep for the duration of the session. A 100 µS rarefaction click stimulus with a rate of 19.1/sec was used to record two-channel (ipsilateral and contralateral) ABRs at stimulus intensities 70, 80, and 90 dB nHL, starting with 90 dB nHL and decreasing the intensity in 10 dB nHL increments. There were two additional recording conditions utilizing a 90 dB nHL click stimulus: one condition employed a rarefaction polarity click stimulus and a stimulus rate of 61.1/sec, the other employed a condensation polarity click stimulus with a click rate of 19.1/sec. This sequence of ABR recordings were initially recorded in the first test ear, followed by the second test ear.

ABR Response Measurements

All response measurements for the ABR were taken on the summed response (i.e., 2048 trials) for each test condition. The absolute latencies of waves I, III and V were measured from the 19.1/sec test conditions at each stimulus intensity. The absolute latency of waves I and III were taken from the center of the peak. In contrast, the absolute latency of wave V was taken from the last point of positivity, or the shoulder of the wave, before it began to slope downward. If there was a clear separation of waves IV and V, then wave V latency was measured on the peak of the wave. If there was a bifid wave V, then the absolute latency measurement for wave V was taken at the center of the response.

In order to calculate peak-to-peak amplitude measurements for waves I and V, wave I' and wave V' were labeled and measured. Wave I' is defined as the major negative trough following wave I. Similarly, wave V' is defined as the major negative trough

occurring within 8 ms of the positive peak of wave V (Oates & Stapells, 1997). Once these measurements were taken, peak-to-peak amplitudes for waves I-I' and V-V' were calculated by subtracting the difference between the amplitude value for the positive peak and the amplitude value occurring at the following negative trough for each of these waves (Hall, 2007).

Calibration

Prior to data collection, the Bio-logic system was calibrated for stimulus intensity, stimulus polarity, and linearity. Equipment required for calibration included a Larson Davis model 824 sound level meter and Larson Davis model 2575 one-inch microphone. The Bio-logic AEP System has a calibration factor of 0 dB nHL = 35 dB SPL. Therefore, this calibration factor was employed. As seen in table 3 below, all of the calibration data was in accordance with these criteria. Additionally, linearity was within normal limits and an appropriate reversal in polarity was seen on the oscilloscope when the stimulus was changed from a rarefaction click stimulus to a condensation click stimulus.

Table 3.

Calibration Intensity Levels.

dB nHL	**Right dB SPL**	**Left dB SPL**
90	125.7	125.2
80	115.1	115.6
70	104.9	105.0

Statistical Analysis

Descriptive statistics (mean, standard deviation, and range) were calculated separately for the ABR response measurements from the left and right ears at each stimulus intensity. For the responses to the three rarefaction click stimuli and the one condensation click stimulus with click rates of 19.1/sec, descriptive statistics were calculated for the following measurements: (1) absolute latencies of waves I, III, and V, (2) IPLs of waves I-III, III-V, and I-V, (3) ILDs of waves V and I-V, and (4) peak-to-peak amplitudes of waves I-I' and V-V'. For the responses to the rarefaction click stimulus presented at the faster stimulus rate (61.1/sec), descriptive statistics were only calculated for wave V latency.

Additionally, a series of 29 independent t-tests were conducted to compare means of the response measurements between right and left ears. An initial alpha level of $p \leq 0.05$ was used to indicate statistical significance. However, a Bonferroni correction was performed to prevent from making a type I error, in which there is said to be a significant finding when in reality, there is no statistically significant difference between measurements. The new corrected alpha level was $p \leq .002$, which was calculated by dividing the original alpha level by the total number of t-tests (.05/29). This was to ensure that response measurements were not found to be statistically different from one another, so that data from the right and left ears could be combined for a total of 40 ABR responses for each recording condition. Finally, a two-way repeated measure analysis of variance (ANOVA) was conducted to examine if there was a significant effect of ear (right vs. left) or click rate (19.1/sec vs. 61.1/sec) on wave V absolute latency. An alpha level of $p \leq .05$ indicated statistical significance for the two-way ANOVA.

CHAPTER 4: RESULTS

The aim of this study was to collect ABR normative data for the Bio-logic Auditory Evoked Potential (AEP) system at Towson University's Hearing and Balance Clinic. The results section will be organized in the following manner. First, results regarding the various latency measurements obtained in this study will be discussed. These response measurements include: the absolute latency values for waves I, III, and V; the interpeak latency values for waves I-III, III-V, and I-V; and the interaural latency differences for wave V and wave I-V. Secondly, the peak-to-peak amplitudes for waves I-I' and V-V', as well as wave V/I amplitude ratio information will be presented. Next, a section on the effects of click rate on wave V absolute latency will be discussed, followed by a section on effects of stimulus polarity on the ABR. Lastly, a section including examples of ABR morphology and replicability of the data will be presented. This final section will also include a summary sheet of the normative data to be used in the Towson University Hearing and Balance Clinic. The organization of this section will be continued in the following discussion section.

A total of 29 independent t-tests were conducted to determine if there were significant differences in the latency and amplitude response measurements between the right and left ears. These t-tests were conducted separately for the results at each stimulus intensity. Results of these t-tests revealed no significant difference between ears for any of the response measures. Therefore, data from the 20 participants were collapsed across ears and the mean data reported below is for a total of 40 ears. More specific information regarding data analysis will discussed below.

ABR Latency Response Measurements

As previously mentioned, the response measurements for latency include: the absolute latencies for waves I, III and V; interpeak latencies for waves I-III, III-V, and I-V; and interaural latency differences for waves V and I-V. Each type of latency measurements will be presented in the subsections below.

Absolute Latency Values of Waves I, III, and V

Table 4 displays the mean and standard deviation values for absolute latencies of waves I, III, and V for click-evoked ABRs recorded at stimulus intensities of 90, 80, and 70 dB nHL. As expected, the mean latency values for all three waves increase as stimulus intensity decreases. The variability in this latency data, reflected in the standard deviation (SD) values, was small with values ranging from 0.08-0.14 ms.

Table 4.

Mean ABR Normative Data for Absolute Latency of Waves I, III, and V in Milliseconds

Stimulus Intensity	Wave I	Wave III	Wave V
90 dB nHL			
Mean	1.49	3.68	5.60
SD	0.09	0.14	0.12
80 dB nHL			
Mean	1.57	3.73	5.69
SD	0.10	0.14	0.12
70 dB nHL			
Mean	1.69	3.80	5.78
SD	0.08	0.12	0.10

Note. n = 40

Figure 14 below displays a visual representation of the mean and SD values for absolute latency shifts as a function of stimulus intensity for waves I, III, and V. Overall, shifts in absolute latency values across this 20 dB nHL range of stimulus intensities (90 dB nHL to 70 dB nHL) were similar across all three waves. Specifically, these three waves had mean absolute latency shifts of approximately 0.15-0.2 ms when stimulus intensity was decreased from 90 dB nHL to 70 dB nHL.

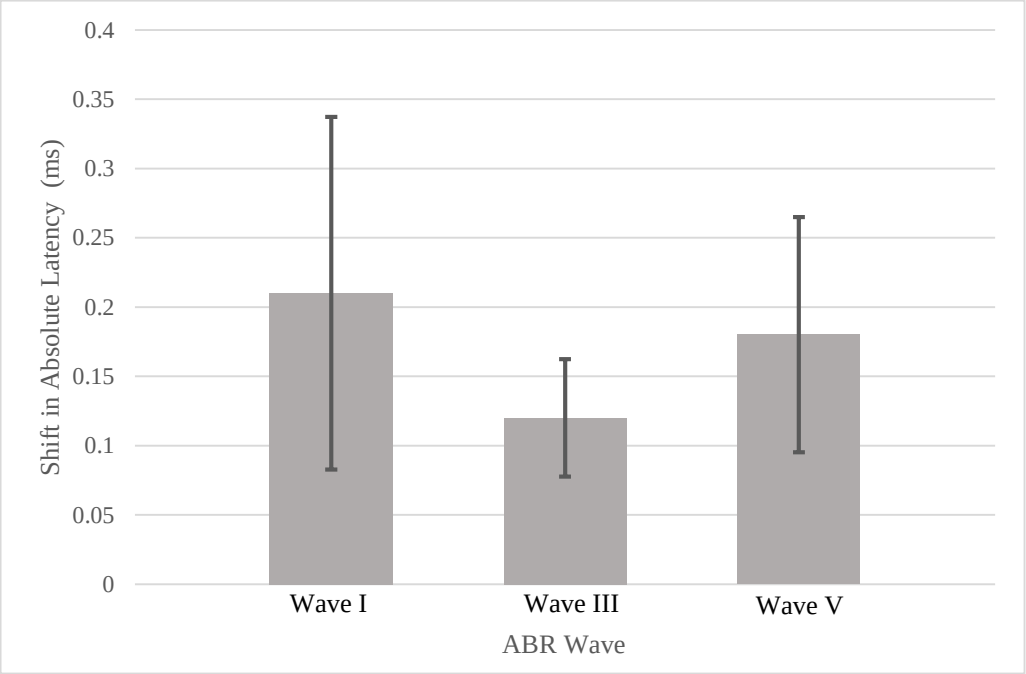

Figure 14. Mean absolute latency shifts for ABR waves I, III, and V when stimulus intensity is decreased from 90 dB nHL to 70 dB nHL. (n = 40)

As previously mentioned, a series of nine independent t-tests were conducted on the absolute latency measure for waves I, III, and V to determine if there were any ear specific differences. The latency values for each wave at each stimulus intensity was evaluated separately. The results of these t-tests revealed no significant difference in

these response measurements between ears for any of the three waves, with p-values ranging from 0.18 to 0.99. Individual absolute latency data from all participants can be found in Appendix D.

Interpeak Latency Values of Measurements I-III, III-V, and I-V.

The descriptive data (mean and SD values) for interpeak latency values of waves I-III, III-V, and I-V are provided in table 5 below. As expected, the interpeak latency measurements remained relatively stable despite changes in stimulus intensity. The variability in these interpeak latency measurements for all nine conditions, reflected in the SD values, was low and ranged from 0.09 – 0.16 ms.

Table 5.

Mean ABR Normative Data for Interpeak Latency of Waves I-III, III-V, and I-V in Milliseconds.

Stimulus Intensity	Wave I-III	Wave III-V	Wave I-V
90 dB nHL			
Mean	2.19	1.93	4.12
SD	0.16	0.09	0.15
80 dB nHL			
Mean	2.16	1.96	4.12
SD	0.16	0.10	0.15
70 dB nHL			
Mean	2.10	1.99	4.09
SD	0.12	0.09	0.12

Note. n = 40

The relationship between interpeak latency and stimulus intensity can be seen below in figure 15. As the figure demonstrates, there is minimal difference in the wave I-

III, wave III-V, and wave I-V interpeak latency values as a function of stimulus intensity. For example, the mean interpeak latency for wave I-V was approximately 4.10 ms for all three stimulus intensities.

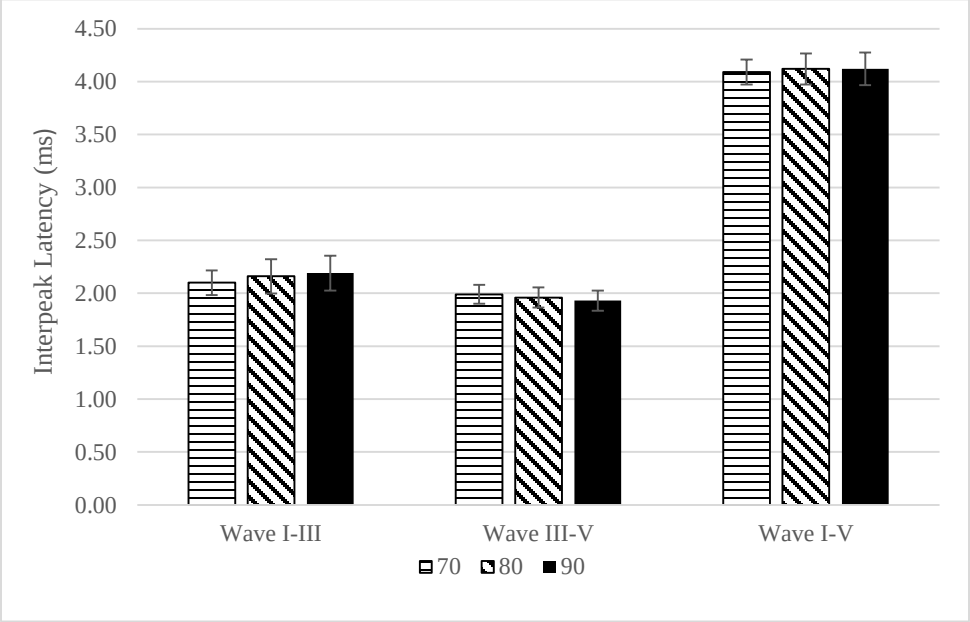

Figure 15. Mean interpeak latencies and standard deviations for measurements I-III, III-V, and I-V in milliseconds as a function of stimulus intensity. (n = 40)

Another series of nine independent t-tests were conducted to compare interpeak latency measurements obtained from responses recorded from the right versus the left ear. Results of these t-tests indicated that there were no significant differences the interpeak latency values measured for the right versus left ears at any of the stimulus intensities. The p-values for these analyses ranged from 0.29 to 0.80. Given these results, data from the right and left ears were combined for a total of 40 ears. Appendix E contains individual interpeak latency data from all 40 ears.

Interaural Latency Differences for Wave V and IPL I-V.

Interaural latency differences for wave V and the I-V interpeak interval were calculated for all 20 participants. If both ears are otologically normal, than these interaural latency values for wave V and for the I-V interpeak latency should not exceed 0.2 ms (Selters & Brackmann, 1977). In this study, the mean interaural latency differences for wave V ranged from 0.02 to 0.03 ms across all three stimulus intensities, as seen in table 6. Similarly, the mean interaural wave I-V latency differences ranged from 0.03 to 0.04 ms. There was little variability seen in these data, with SD values ranging from 0.04 to 0.05 ms. All of the 20 participants in the present study had interaural latency differences for either wave V or I-V interpeak latency that were less than 0.2 ms, as seen in Appendix F.

Table 6.

Mean ABR Normative Data for Interaural Latency Values in Milliseconds.

Stimulus Intensity	**Wave V**	**Wave I-V**
90 dB nHL		
Mean	0.02	0.03
SD	0.04	0.04
80 dB nHL		
Mean	0.03	0.04
SD	0.04	0.04
70 dB nHL		
Mean	0.03	0.04
SD	0.05	0.04

Note. n = 20

Figure 16 includes a graphical representation of interaural latency differences for wave V and the I-V interpeak latency across all three stimulus intensities. As seen in the figure, the mean interaural latency differences for both measurements were well below 0.2 ms criteria, which has been marked with a horizontal bold line. For example, the mean interaural latency differences for wave V and the I-V interpeak value at 90 dB nHL were 0.02 and 0.03 ms, respectively.

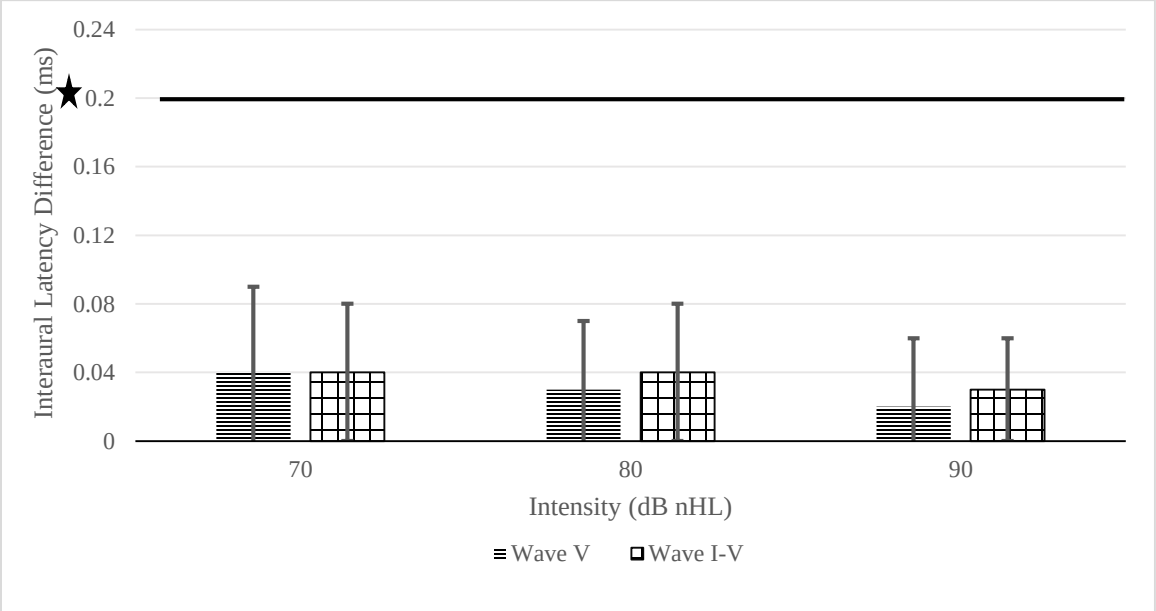

Figure 16. Mean interaural differences in milliseconds for waves V and I-V as a function of stimulus intensity. The bold line at 0.2 ms indicates the criteria for significant interaural differences for these two response measurements (n = 20).

ABR Peak-to-Peak Amplitude of Wave I-I', Wave V-V', and Wave V/I Amplitude Ratio

The peak-to-peak wave I-I' and wave V-V' amplitudes were measured and used to calculate the wave V/I amplitude ratios for all 40 ears. Table 4 below provides mean and standard deviation values for all three amplitude measurements at stimulus intensities of 90, 80, and 70 dB nHL. As expected, the mean wave I-I' and wave V-V' amplitudes decrease as stimulus intensity decreases. For instance, the mean wave V-V' amplitude decreased from 0.61 µV to 0.41 µV when stimulus intensity decreased from 90 dB nHL to 70 dB nHL. The extent of the reduction in amplitude was essentially the same for waves I-I' and V-V'. The variability seen in the peak-to-peak amplitude measurements for waves I-I" and V-V', as reflected in the SD values, was low (ranging from 0.11 to 0.22). The SD values for these amplitude measures, however, are slightly larger than those of absolute latency measurements. These higher rates of variability for peak-to-peak amplitude values are expected, since amplitude is generally a more variable response measure than is absolute latency (Hall, 2007).

Otologically normal ears typically have wave V/I amplitude ratios that are greater than 0.5 µV (Hall, 2007). In the present study, the mean wave V/I amplitude ratios exceeded 0.5 µV at all three stimulus intensities. The variability in the wave V/I amplitude ratio measurements was approximately 3 times greater than for the absolute peak-to-peak amplitude measures.

Table 7.

Mean ABR Normative Data for Peak-to-peak Amplitudes and Wave V/I Ratio Values in Microvolts.

Stimulus Intensity	Wave I-I'	Wave V-V'	Wave V/I
90 dB nHL			
Mean	0.51	0.61	1.33
SD	0.18	0.22	0.61
80 dB nHL			
Mean	0.48	0.48	1.06
SD	0.15	0.16	0.47
70 dB nHL			
Mean	0.31	0.41	1.41
SD	0.11	0.15	0.62

Note. n = 40

Figure 17 below displays the mean wave V/I amplitude ratios at 70, 80, and 90 dB nHL. All three of these mean V/I amplitude ratio values far exceeded the minimally acceptable criteria of 0.5 μV for normal hearing subjects. The bold line in this figure represents the minimum acceptable wave V/I ratio criteria in normal-hearing subjects. This finding was expected, since participants included in this study were normally-hearing adults with a negative history of otoneurologic pathology (Hall, 2007).

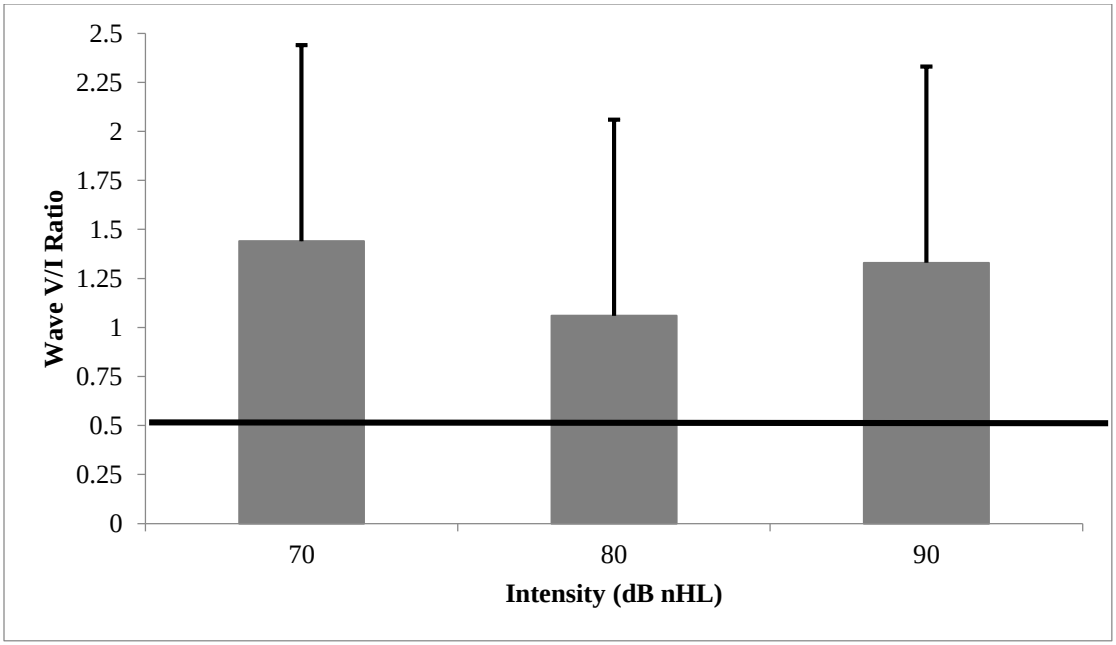

Figure 17. Means and standard deviations for wave V/I ratios recorded in microvolts (μV) (n = 40).

A series of 9 t-tests was conducted to compare mean values for wave I-I' and wave V-V' peak-to-peak amplitude measurements as well as wave V/I amplitude ratio to determine if there were any specific ear differences. Results of these t-tests indicated that there were no significant differences between any of these amplitude measurements for the right verses the left ear. The p-values ranged from 0.36 to 0.98. Therefore, the amplitude data from the right and left ears were combined for a total of 40 ears. Individual amplitude data can be seen in Appendix G.

Effects of Click Rate on the Absolute Latency of Wave V

Absolute latency values for wave V were measured from ABRs recorded to 90 dB nHL click stimuli presented at both a slower click rate test condition (19.1/sec) and a

faster click rate test condition (61.1/sec). Table 8 displays the mean and SD values for the absolute latency of wave V for both click rate conditions. It also contains the mean latency shift in wave V as a function of stimulus rate. This shift in wave V latency as a function of stimulus rate was calculated by subtracting the wave V absolute latency value of the faster rate condition from the wave V absolute latency value of the slower rate condition. This measurement was calculated for all 40 ears. As seen in the table, the mean absolute latency of wave V increased by 0.39 seconds in response to a faster click rate. The variability in the data, shown in the SD values, was low for all test conditions, with values ranging from 0.08 to 0.12 ms.

Table 8.

Effect of Click Rate on Wave V Absolute Latency in Milliseconds

	Slow Rate (19.1/sec)	**Fast Rate (61.1/sec)**	**Shift in Wave V Latency as fnct. of click rate**
90 dB nHL			
Mean	5.60	5.99	0.39
SD	0.12	0.12	0.08

Note. n = 40

As anticipated, the absolute latency of wave V shifted between the slower and faster rate test conditions, as seen in figure 18 below. The mean wave V absolute latencies from the 19.1 and 61.1/sec conditions were 5.6 and 5.99 ms, respectively. The mean shift in wave V latency values between these two rate conditions was 0.39 ms.

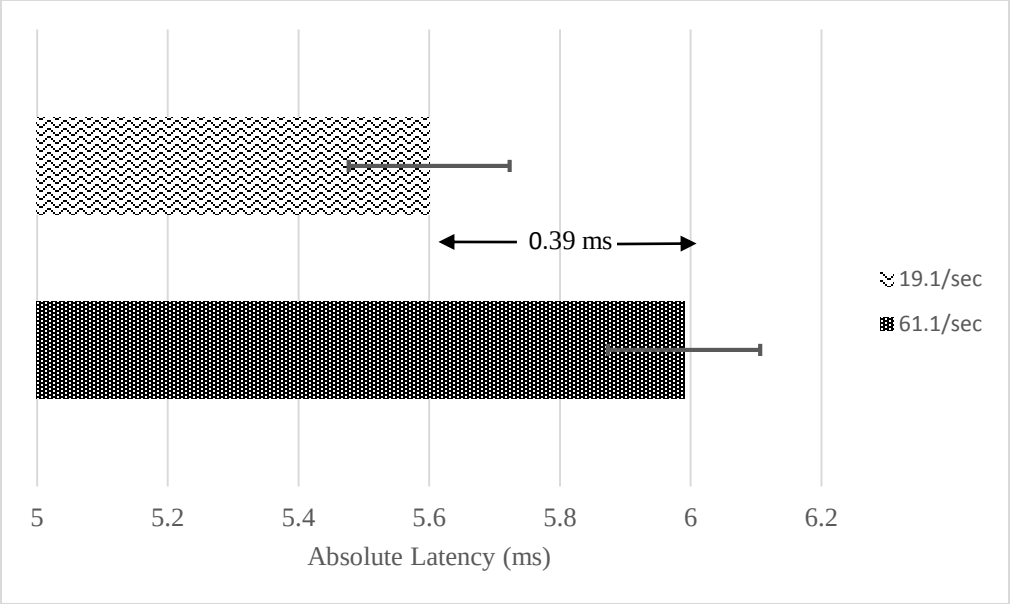

Figure 18. The mean wave V absolute latency values for the slower (19.1/sec) and faster click rate (61.1/sec) test conditions. This figure also shows the mean wave V latency shift between these two test conditions. (n = 40).

Two separate t-tests were conducted to compare the mean wave V latency values for the slower and faster rate test conditions to determine if there were any ear specific differences. Results of these t-tests indicated that there were no significant differences in wave V latency shift between ears for the slower or faster test condition, with p-values of .65 (slow rate) and .55 (faster rate). Therefore, results from right and left ears were combined for a total of 40 ears. Individual data for wave V latency shifts in response to increased click rate can be found in Appendix H. Additionally, a two-way ANOVA was conducted to determine if there were significant effects of ear (right vs. left) on mean wave V absolute latency, of click rate (19.1/sec vs. 61.1/sec) on mean wave V absolute latency, and if there was a significant interaction between these two factors. As expected,

there was a significant main effect for rate such that the mean wave V absolute latency was significantly longer for the faster (61.1/sec) test condition in comparison to the slower (19.1/sec) test condition, $F(1,76) = 203.77$, $p \leq .05$. There were no significant ear effects nor any significant interaction between ear and rate, $F(1,76) = 0.56$, $p \leq .05$, $F(1,76) = .01$, $p \leq .05$, respectively.

Effects of Stimulus Polarity on the ABR

ABRs were recorded separately to both a rarefaction and a condensation click stimulus at 90 dB nHL for all 40 ears. As discussed previously, individuals with ANSD typically present with a reversal in the polarity of the neural ABR waves in response to a condensation versus a rarefaction click stimulus. If a reversal in polarity of the neural response occurs when switching the polarity of the click stimulus, this finding indicates that the response is not neural in nature (Hood, 1998). None of the participants had responses to the condensation click stimulus that reversed in polarity when compared to their responses to the rarefaction click stimulus.

Figure 19 below shows an example of one participant's ABRs in response to a 90 dB nHL rarefaction click stimulus and a 90 dB nHL condensation click stimulus. As seen in the figure, this individual's ABR waves have the same polarity for both the rarefaction and condensation stimuli.

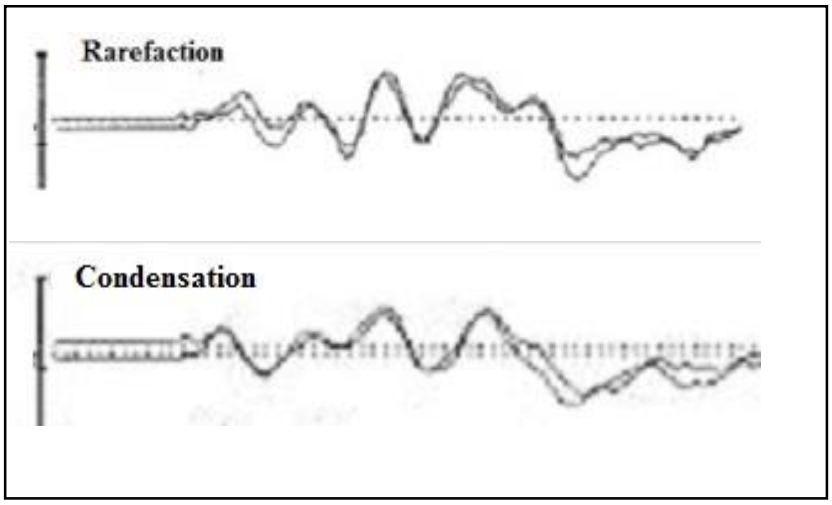

Figure 19. One participant's ABRs in response to 90 dB nHL rarefaction click stimuli (top tracings) and 90 dB nHL condensation click stimuli (lower tracings).

ABR Waveform Morphology and Replicability

Figure 20 below provides examples of two individual subjects' ABR waveforms. The top two tracings are from one participant with good ABR waveform morphology and good replicability. For this subject, waves I, III, and V are clearly defined and occur at appropriate absolute latencies for an adult with normal hearing. Both averaged responses appear almost identical to one another. There are no apparent latency or amplitude differences between the two averaged trials. Only two replications were required from this participant to obtain repeatable responses.

In contrast, the bottom two tracings in figure 20 were recorded from a participant with poorer ABR waveform morphology and replicability, especially for waves I and III. For this individual, the peak-to-peak amplitude of wave I-I' is considerably smaller in the

first tracing compared to the second tracing. Additionally, wave III is poorly formed in the first tracing, while it is more clearly identifiable in the second tracing. This individual required four replications before two repeatable waveforms could be identified. The vast majority (n=17) of the 20 participants in this study had good waveform morphology and replicability, with only three participants requiring more than three ABR replications.

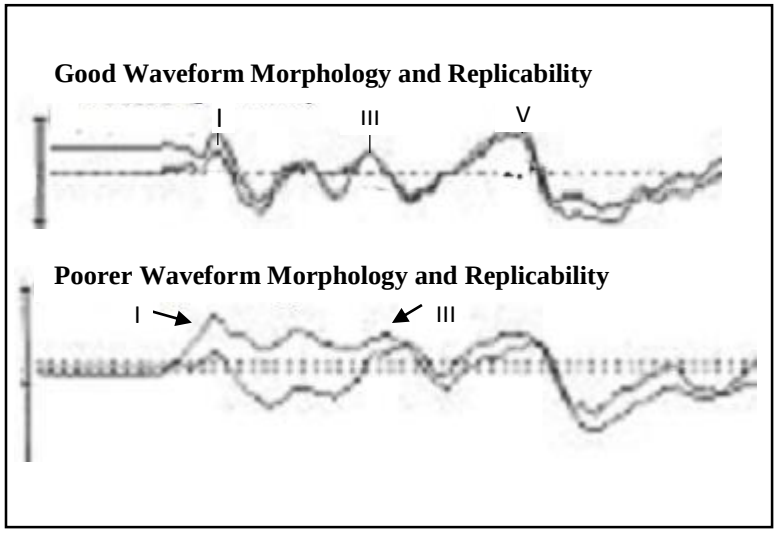

Figure 20. An example of one subject's good ABR waveform morphology and replicability (top tracings) and another subject's poorer ABR waveform morphology and replicability (lower tracings). All responses were recorded to 90 dB nHL rarefaction click stimuli.

ABR Normative Data Summary Sheet

The normative data collected during this study was used to calculate a summary sheet. This summary sheet is a concise reference of the normative data recorded from the Bio-logic AEP system for student clinicians and teachers to utilize while testing patients

at the Towson University Hearing and Balance Center. The Bio-logic AEP normative data summary sheet can be seen in Appendix I.

CHAPTER 5: DISCUSSION

The discussion section will be organized in a similar fashion as the results section. Two additional topics will also be covered in the discussion section. These are: 1) the importance of calibration for AEP units, and 2) the necessity of collecting equipment-specific ABR normative data.

ABR Latency Response Measurements

Absolute Latency of Waves I, III, and V.

During the present study, normative data was established for the absolute latencies of waves I, III, and V recorded to click stimuli presented at intensities of 90, 80, and 70 dB nHL on the Bio-logic AEP System. As expected, our results revealed that as stimulus intensity decreased the mean absolute latencies for waves I, III and V increased. Specifically there was approximately a 0.15- 0.2 ms increase in latency for all three waves as the intensity of the click was decreased from 90 to 70 dB nHL.

Table 9 compares the mean absolute latency values for waves I, III, and V obtained in the present study to normative ABR latency data from two published sources by Hood (1998) and Beattie (1988). The variability present in this normative data, reflected in the SD values, is also included in this table, as well as the range of acceptable latency values for each wave at each stimulus intensity. The ranges represent 2.5 SD above and below the mean. In both of these published studies, the ABRs were recorded to rarefaction click stimuli at moderate to high stimulus intensities (70-90 dB nHL) similar

to those employed in the present study. The analog bandpass filters and length of the post stimulus analysis window were similar across studies. The only parameter in the Beattie study which differed from the present study was a somewhat slower click rate (9.2/sec versus 19.1/sec in the present study). The subsequent tables in the discussion section follow the same organization.

The mean absolute latency values for waves I, III and V in the present study are in good agreement with the mean data reported by Hood and Beattie. Hood reported slightly earlier mean wave V latencies at both 90 and 70 dB nHL in comparison to the present study, however, the range of acceptable absolute latencies are similar between studies. Hood's normative data was collected on a smaller sample size of 14 female participants, which may explain, at least in part, these mean wave V latency differences. Dempsey et al. (1986) and Don et al. (1993) have reported that females have earlier absolute latencies versus males to the same click stimuli. In addition, the mean absolute latency values for waves I, III and V for the Beattie data at the lower stimulus intensity are also somewhat earlier in comparison to the present study. This is likely due to the fact that they were recorded at 75 dB nHL versus 70 dB nHL for both the present study and the Hood study. Lastly, the variability in the absolute latency measurements for waves I, III and V, reflected in the SD values, was low for all three sets of normative data at both 90 and 70 dB nHL.

Table 9.

A Comparison of Mean ABR Absolute Latencies in Milliseconds for Waves I, III, and V Across Three Sources.

Latency Measurement	Present	Hood, 1998	Beattie, 1988
	90 dB nHL		
Wave I			
Mean	1.49	1.53	1.39
SD	0.09	0.11	0.10
(+/- 2.5 SD)	(1.27-1.72)	(1.26-1.81)	(1.14-1.64)
Wave III			
Mean	3.68	3.58	3.58
SD	0.14	0.09	0.17
(+/- 2.5 SD)	(3.33-4.03)	(3.36-3.81)	(3.16-4.01)
Wave V			
Mean	5.60	5.37	5.63
SD	0.12	0.12	0.18
(+/- 2.5 SD)	(5.30-5.90)	(5.07-5.67)	(5.18-6.08)
	70 dB nHL		
Wave I			
Mean	1.69	1.82	1.52
SD	0.08	0.17	0.08
(+/- 2.5 SD)	(1.49-1.89)	(1.39-2.25)	(1.32-1.72)
Wave III			
Mean	3.80	3.85	3.56
SD	0.12	0.13	0.14
(+/- 2.5 SD)	(3.50-4.10)	(3.53-4.18)	(3.21-3.91)
Wave V			
Mean	5.78	5.64	5.61
SD	0.10	0.16	0.15
(+/-2.5 SD)	(5.53-6.03)	(5.24-6.04)	(5.24-5.99)

Interpeak Latencies for Measurements I-III, III-V, and I-V.

In the present study, normative data was also established for the interpeak latencies of waves I-III, III-V, and I-V at 90, 80, and 70 dB nHL. As expected, the interpeak latency values for each interpeak latency measurements (i.e., I-III, III-V and I-V) in the present study were similar across stimulus intensities.

Table 10 below displays a comparison of the mean interpeak latency data in the present study to that obtained by Hood (1998) and Beattie (1988).

The mean interpeak latency values for waves I-III, III-V and I-V in the present study are in relatively good agreement with the mean interpeak latency data reported by these two published sources. This finding is true at both stimulus intensities. The variability in the interpeak latency data was minimal across studies, with SD values ranging from 0.09 to 0.16.

Table 10.

ABR Mean Interpeak Latencies in Milliseconds for I-III, III-V, and I-V From Three Sources.

Latency Measurement	Present	Hood, 1998	Beattie, 1988
	90 dB nHL		
IPL I-III			
Mean	2.19	2.05	2.19
SD	0.16	0.14	--
(+/- 2.5 SD)	(1.79-2.59)	(1.70-2.40)	--
IPL III-V			
Mean	1.93	1.79	2.05
SD	0.09	0.14	--
(+/- 2.5 SD)	(1.74-2.19)	(1.44-2.14)	--
IPL I-V			
Mean	4.12	3.84	4.24
SD	0.15	0.16	--
(+/- 2.5 SD)	(3.75-4.50)	(3.44-4.24)	--
	70 dB nHL		
IPL I-III			
Mean	2.10	2.03	2.04
SD	0.08	0.11	--
(+/- 2.5 SD)	(1.80-2.40)	(1.76-2.31)	--
IPL III-V			
Mean	1.99	1.79	2.05
SD	0.09	0.12	--
(+/- 2.5 SD)	(1.69-2.29)	(1.49-2.09)	--
IPL I-V			
Mean	4.09	3.82	4.09
SD	0.12	0.11	--
(+/-2.5 SD)	(3.79-4.39)	(3.55-4.10)	--

Note. Beattie's (1988) IPL values were calculated based in the mean absolute latencies reported in the study. SD values were not available for these measurements.

Interaural Latency Differences for Wave V and Interpeak Latency I-V.

In the present study, all participants had interaural latency differences for wave V and the I-V interpeak interval of less than 0.2 ms, with values ranging from 0.02 to 0.04 ms. This finding is in excellent agreement with previous research. Don and Kwong (2009) and Selters and Brackmann (1977) have shown that individuals with normal hearing and a negative history of otologic involvement have interaural latency differences for these two measures which are less than 0.2 ms.

ABR Amplitude Measurements

Peak-to-peak Amplitudes of Waves I-I' and V-V'.

In the present study, the mean peak-to-peak amplitude values for waves I-I' and V-V' were calculated at each of the three stimulus intensities. These mean peak-to-peak amplitudes for both waves decreased by approximately 0.2 µV as stimulus intensity decreased from 90 to 70 dB nHL. As expected, mean wave V-V' peak-to-peak amplitudes were consistently larger than wave I-I' peak-to-peak amplitudes.

Table 11 below displays a comparison of the mean peak-to-peak amplitudes for waves I-I' and V-V' for the present study and for the Beattie (1988) study. No normative data on peak to peak amplitudes was available in the Hood (1998) study. The trends seen in the amplitude data from both sources are in good agreement. Specifically, the peak to peak amplitude values for waves I-I' and V-V' decrease with a decrease in stimulus intensity in both studies. Secondly, the amplitude of wave V-V' is consistently larger than the amplitude of wave I-I' at both stimulus intensities; and there is approximately a 0.15 to 0.20 µV decrease in amplitude for both waves as the click intensity was decreased

from 90 to 70/75 dB nHL. Lastly, there is little variability in these mean amplitude values for either study.

Table 11.

ABR Mean Peak-to-Peak Amplitude Measurements in Microvolts for Waves I-I' and V-V' From Two Sources.

ABR Wave	Present Study	Beattie, 1988
	90 dB nHL	
Wave I-I'		
Mean	0.51	0.42
SD	0.18	0.18
Wave V-V'		
Mean	0.61	0.50
SD	0.22	0.18
	70 dB nHL	
Wave I-I'		
Mean	0.31	0.29
SD	0.11	0.14
Wave V-V'		
Mean	0.41	0.36
SD	0.15	0.13

Wave V/I Ratio.

The mean wave V/I ratios reported in the present study ranged from 1.06 to 1.41 µV across the three stimulus intensities. All 20 subjects had wave V/I ratios above 0.5 µV. Hall (2007) stated that the wave V/I ratio for a normal-hearing individual with no otologic abnormalities should be greater than or equal to 0.5 µV. Furthermore, a wave V/I ratio less than 0.5 µV typically means that wave V has an abnormally small amplitude, indicating the presence of a retrocochlear pathology (Hall, 2007).

Effects of Click Rate on the Absolute Latency of Wave V

In the present study, a mean wave V latency shift of 0.39 ms was observed when click rate was increased from 19.1/sec to 61.1/sec. Results of a two-way ANOVA indicated that the mean wave V absolute latency between the 19.1/sec and 61.1/sec click rates were significantly different. This finding is in good agreement with previous findings. Picton, Stapells, & Campbell (1981) reported a mean wave V latency shift of 0.1 ms for every 10 fold increase in stimulus rate. In the present study, there was approximately a four-fold increase in click rate when the rate was changed from 19.1/sec to 61.1/sec. Therefore, a wave V absolute latency shift of about 0.40 ms was expected.

Effects of Stimulus Polarity on the ABR

No participant in the present study had ABR waveforms that reversed in polarity when the polarity of the click stimulus was changed from rarefaction to condensation. Results from the present study regarding the effects of stimulus polarity on the ABR are consistent with what has been reported in the literature. According to Hood (1998), switching the click polarity from rarefaction to condensation should not impact the polarity of the ABR response in otologically normal individuals. If the ABR waveform polarity reverses when stimulus polarity is switched, then the response is not a true neural response, but a mechanical response representing the traveling wave of the basilar membrane (Hood, 1998; Norrix & Velenovsky, 2014).

Calibrating ABR Equipment

When collecting ABR normative data, calibrating the auditory evoked potential equipment is a critical first step. Calibrating the stimulus ensures that it is being delivered at the correct intensity and polarity. Consequently, it can be assumed that the ABR measurements elicited with a calibrated stimulus are accurate (Don & Kwong, 2009). Click stimuli in the present study were calibrated for intensity, linearity, and polarity. A Larson Davis CAL 250 SLM with a peak-hold feature was used to calibrate for intensity and linearity. The SPLs that were measured for all three stimulus intensities were within appropriate tolerance levels specified by the Biologic AEP system's manufacturer. Additionally, linearity of the click stimuli was assessed by decreasing the intensity of the stimulus in 10 dB nHL increments and recording the subsequent 10 dB changes in the SPL readings. Polarity of the stimulus was verified by separately playing a rarefaction click stimulus and a condensation click stimulus through an oscilloscope. The rarefaction click produced a square wave with an initial negative pulse, followed by a positive pulse. In contrast, the condensation click produced a square wave with the opposite polarity, indicating that both polarities were accurate for the Biologic AEP equipment.

Collecting Normative Data

It is important for clinics and other facilities that perform ABR testing to collect their own equipment-specific normative data. Factors such as equipment differences and testing environment can have an impact on ABR measurements. Therefore, measurements that are considered normal on one piece of equipment (i.e. Biologic AEP system) at one facility might not be the same on the same piece of equipment at another

facility. By collecting ABR measurements on a group of young normal hearing individuals with a negative otoneurologic history, facilities can ensure that patient ABR results for this clinical population are being compared to accurate normative data specific to their equipment and testing environment.

APPENDICES

APPENDIX A

IRB Approval Letter

TOWSON UNIVERSITY

APPROVAL NUMBER: 16-A046

To: Tressa Lichtfuss
9869 Softwater Way
Columbia MD 21046 ACT

From: Institutional Review Board for the Proctection of Human Subjects Debi Gartland,Chair

Date: Thursday, November 19, 2015

RE: Application for Approval of Research Involving the Use of Human Participants

Office of Sponsored Programs
& Research

Towson University
8000 York Road
Towson, MD 21252-0001

t. 410 704-2236
f. 410 704-4494
www.towson.edu/ospr

Thank you for submitting an Application for Approval of Research Involving the Use of Human Participants to the Institutional Review Board for the Protection of Human Participants (IRB) at Towson University. The IRB hereby approves your proposal titled:

The Auditory Brainstem Response (ABR): A Collection of Normative Data Using the Bio-logic AEP system

If you should encounter any new risks, reactions, or injuries while conducting your research, please notify the IRB. Should your research extend beyond one year in duration, or should there be substantive changes in your research protocol, you will need to submit another application for approval at that time.
We wish you every success in your research project. If you have any questions, please call me at (410) 704-2236.

CC: Peggy Korczak
File

TOWSON UNIVERSITY

Date: Thursday, November 19, 2015

NOTICE OF APPROVAL

TO: Tressa Lichtfuss **DEPT:** ASLD

PROJECT TITLE: *The Auditory Brainstem Response (ABR): A Collection of Normative Data Using the Bio-logic AEP system*

SPONSORING AGENCY: None

APPROVAL NUMBER: 16-A046

The Institutional Review Board for the Protection of Human Participants has approved the project described above. Approval was based on the descriptive material and procedures you submitted for review. Should any changes be made in your procedures, or if you should encounter any new risks, reactions, injuries, or deaths of persons as participants, you must notify the Board.

A consent form: [✓] is [ ] is not required of each participant

Assent: [ ] is [✓] is not required of each participant

This protocol was first approved on: 19-Nov-2015

This research will be reviewed every year from the date of first approval.

Debi Gartland,Chair
Towson University Institutional Review Board

APPENDIX B

Department of Audiology, Speech-Language Pathology, and Deaf Studies

Informed Consent and Disclosure Agreement

Project Title:

The Auditory Brainstem Response (ABR): A Collection of Normative Data Using the Bio-logic AEP system

Principal Investigator: Tressa Lichtfuss, B.S. **Phone:** 410-491-4892

Purpose of the Study:

The purpose of the proposed study is to collect normative data for the ABR on the Bio-logic AEP system at the Towson University Hearing and Balance Center. The otoneurologic ABR is a clinical test routinely used to assess the health of the auditory nerve and the brainstem. This normative data will be used by student clinicians and clinical supervisors as a reference when conducting otoneurologic ABRs at the Towson University Hearing and Balance Center.

Eligibility:

Participants must be between the ages of 20 and 30 years to be included in the study. They must have normal hearing and normal middle ear function. Normal hearing will be assessed by conducting pure tone audiometry from frequencies 250 to 8000 Hz. Hearing thresholds must be ≤ 15 dB nHL. Middle ear status will be assessed with tympanometry and contralateral acoustic reflexes for both ears. Normal tympanometry will be defined by middle ear pressure ranging from +50 to -150 daPa, static compliance values ranging from 0.2-1.4 ml, and ear canal volumes ranging between 0.6-1.6 ml. Acoustic reflexes will be considered normal when they are present within the 90th percentile at 500 Hz, 1000 Hz, and 2000 Hz. If any participant presents with abnormal hearing or middle ear function, they will not be included in the collection of ABR normative data.

Procedures:

Test sessions will take between 2 and 3 hours. The participant will be asked to fill out a case history questionnaire prior to testing. Then, a visual examination of the outer ear/ear canal will be performed, followed by an assessment of middle ear function. A test of hearing sensitivity will be performed to test for normal hearing. This test requires for the participant to press a response button every time they hear a tone

presented. If results are normal, the participant will undergo otoneurologic ABR testing with click sounds. During this portion of the study, participants will be encouraged to relax and/or sleep in a reclining chair.

Risks/Discomfort:

There are minimal risks involved in this study. No physical discomfort should occur due to testing. The Auditory Brainstem Response is a test commonly used in clinical settings for patients of all ages. This is a noninvasive test that involves placing four electrodes on the scalp, the forehead, and both earlobes. Click sounds will be presented to the participant at various loudness levels. These intensity levels are nonhazardous and are routinely used in clinical settings. However, should the participant feel any discomfort from the click sounds, they should tell the primary investigator so that testing can be stopped.

Benefits:

Results from this study should provide normative data on the otoneurologic ABR that will benefit both students and faculty of the Audiology Department at Towson University. Benefits for the participant include a free hearing test as well as free otoneurologic ABR testing. The participant will be informed of their test results upon the conclusion of the test session.

Right to Refuse or Withdraw:

Participation in this study is entirely voluntary. Should the participant feel the need to withdraw from the study after agreeing to participate, they are welcome to do so. This decision will in no way effect future services that may be provided to the participant at the Towson University Hearing and Balance Center.

Cost Compensation:

Participation in this study will involve no costs or payments for the participant.

Confidentiality:

All information collected during the study period will be kept strictly confidential. Participants will be identified through a random five-digit identification numbers. Only the primary investigator will be aware of participants' identity. No publications or reports from this project will include identifying information on any participant. If you agree to join this study, please sign your name below.

_____ I have read and understood the information on this form.

_____ I have had the information on this form explained to me.

_____

Participant Printed Name

_____ _____

Participant's Signature Date

_____ _____

Principal Investigator Date

If you have any questions regarding this study please contact Dr. Smyth of the Hoffer Clinic at (301) 468-5924 or the Institutional Review Board Chairperson, Dr. Debi Gartland, Office of University Research Services, 8000 York Road, Towson University, Towson, Maryland 21252; phone (410) 704-2236.

THIS PROJECT HAS BEEN REVIEWED BY THE INSTITUTIONAL REVIEW BOARD FOR THE PROTECTION OF HUMAN PARTICIPANTS AT TOWSON UNIVERSITY.

IRB approval number _____

APPENDIX C

Subject # _____

Date _____

Otoneurologic Case History Form

Please check either "yes" or "no" in response to the following questions. If your answer is "yes" to one or more question(s), please explain in the comments section below.

1. Do you have a diagnosed hearing loss? Yes____ No____
2. Do you have a history of chronic ear infections? Yes____ No____
3. Are you currently experiencing any ear pain? Yes____ No____
4. Do you currently or have you previously experienced chronic ringing, humming, or buzzing in your ears? Yes____ No____
5. Do you currently experience feelings of aural fullness? Yes____ No____
6. Do you have any known ear-related pathologies? Yes____ No____
7. Do you have any known syndromes/diagnoses associated with hearing loss? Yes____ No____
8. Have you undergone any ear-related surgeries, or have you had any surgeries performed around/near the ear(s)? Yes____ No____
9. Do you currently experience feelings of dizziness or imbalance? Yes____ No____
10. Have you ever had a traumatic brain/head injury? Yes____ No____
11. Have you previously been diagnosed with a neurological condition? Yes____ No____

Comments:

_____
_____
_____
_____

APPENDIX D

ABR Absolute Latency Raw Data

		90 dB nHL			80 dB nHL			70 dB nHL		
SUBJ	**EAR**	**W I**	**WIII**	**WV**	**WI**	**WIII**	**WV**	**WI**	**WIII**	**WV**
1	R	1.39	3.83	5.51	1.45	3.89	5.64	1.70	3.89	5.76
	L	1.39	3.83	5.57	1.51	3.89	5.70	1.70	3.89	5.76
2	R	1.45	3.64	5.57	1.51	3.83	5.64	1.64	3.89	5.70
	L	1.45	3.70	5.57	1.45	3.89	5.64	1.64	3.89	5.70
3	R	1.33	3.45	5.45	1.39	3.45	5.51	1.51	3.51	5.70
	L	1.26	3.58	5.45	1.33	3.58	5.51	1.51	3.58	5.64
4	R	1.58	3.64	5.64	1.64	3.76	5.70	1.70	3.83	5.76
	L	1.64	3.76	5.76	1.70	3.89	5.82	1.76	3.95	5.89
5	R	1.58	3.39	5.32	1.58	3.45	5.45	1.70	3.64	5.57
	L	1.58	3.39	5.32	1.58	3.45	5.45	1.64	3.58	5.51
6	R	1.39	3.83	5.82	1.45	3.89	5.89	1.64	3.95	5.95
	L	1.39	3.83	5.82	1.45	3.89	5.89	1.64	3.89	5.95
7	R	1.45	3.64	5.51	1.51	3.64	5.57	1.64	3.70	5.76
	L	1.45	3.64	5.51	1.51	3.70	5.64	1.64	3.70	5.76
8	R	1.64	3.70	5.64	1.70	3.76	5.70	1.83	3.76	5.89
	L	1.64	3.70	5.64	1.70	3.70	5.70	1.83	3.76	5.82
9	R	1.58	3.76	5.51	1.64	3.76	5.57	1.83	3.83	5.76
	L	1.58	3.76	5.51	1.64	3.70	5.57	1.83	3.89	5.76
10	R	1.45	3.70	5.70	1.51	3.70	5.76	1.64	3.76	5.82
	L	1.39	3.76	5.64	1.45	3.76	5.76	1.64	3.76	5.89
11	R	1.51	3.87	5.64	1.64	3.83	5.70	1.70	3.83	5.82
	L	1.51	3.83	5.70	1.64	3.89	5.76	1.70	3.89	5.89
12	R	1.45	3.51	5.51	1.64	3.64	5.57	1.76	3.70	5.70
	L	1.45	3.64	5.57	1.58	3.64	5.64	1.76	3.83	5.70
13	R	1.51	3.39	5.45	1.64	3.45	5.51	1.70	3.64	5.64
	L	1.58	3.51	5.51	1.70	3.64	5.64	1.76	3.83	5.76
14	R	1.39	3.64	5.57	1.51	3.64	5.64	1.76	3.76	5.70
	L	1.51	3.58	5.57	1.58	3.58	5.64	1.70	3.70	5.76
15	R	1.64	3.83	5.70	1.70	3.83	5.70	1.83	3.83	5.82
	L	1.64	3.83	5.70	1.70	3.83	5.76	1.76	3.89	5.82
16	R	1.39	3.76	5.64	1.51	3.83	5.76	1.70	3.89	5.82
	L	1.39	3.76	5.70	1.45	3.83	5.76	1.64	3.89	5.82
17	R	1.45	3.76	5.82	1.51	3.76	5.89	1.64	3.89	5.95
	L	1.45	3.76	5.82	1.51	3.76	5.89	1.70	3.95	5.95
18	R	1.51	3.76	5.64	1.64	3.83	5.76	-	3.95	-
	L	1.51	3.76	5.64	1.64	3.89	5.82	1.70	3.95	5.89
19	R	1.51	3.64	5.70	1.58	3.76	5.76	1.64	3.76	5.76
	L	1.51	3.70	5.70	1.58	3.76	5.82	1.70	3.83	5.89
20	R	1.51	3.45	5.57	1.58	3.51	5.64	1.64	3.58	5.70
	L	1.51	3.58	5.57	1.58	3.58	5.64	1.64	3.58	5.70

APPENDIX E

ABR Interpeak Latency Raw Data

		90 dB nHL			80 dB nHL			70 dB nHL		
SUBJ	**EAR**	**W I-III**	**W III-V**	**W I-V**	**W I-III**	**W III-V**	**WI-V**	**W I-III**	**W III-V**	**W I-V**
1	R	2.44	1.69	4.13	2.44	1.75	4.19	2.19	1.88	4.06
	L	2.44	1.75	4.19	2.38	1.81	4.19	2.19	1.88	4.06
2	R	2.19	1.94	4.13	2.31	1.81	4.13	2.25	1.81	4.06
	L	2.25	1.87	4.13	2.44	1.75	4.19	2.25	1.81	4.06
3	R	2.13	2.00	4.13	2.06	2.06	4.13	2.00	2.19	4.19
	L	2.31	1.88	4.19	2.25	1.94	4.19	2.06	2.06	4.13
4	R	2.06	2.00	4.06	2.13	1.94	4.06	2.13	1.94	4.06
	L	2.13	2.00	4.13	2.19	1.94	4.13	2.19	1.94	4.13
5	R	1.81	1.94	3.75	1.88	2.00	3.88	1.94	1.94	3.87
	L	1.81	1.94	3.75	1.88	2.00	3.88	1.94	1.94	3.87
6	R	2.44	2.00	4.44	2.44	2.00	4.44	2.31	2.00	4.31
	L	2.44	2.00	4.44	2.44	2.00	4.44	2.25	2.06	4.31
7	R	2.19	1.88	4.06	2.13	1.94	4.06	2.06	2.06	4.13
	L	2.19	1.88	4.06	2.19	1.94	4.13	2.06	2.06	4.13
8	R	2.06	1.94	4.00	2.06	1.94	4.00	1.94	2.13	4.06
	L	2.06	1.94	4.00	2.00	2.00	4.00	1.94	2.06	4.00
9	R	2.19	1.75	3.94	2.13	1.81	3.94	2.00	1.94	3.94
	L	2.19	1.75	3.94	2.06	1.87	3.94	2.06	1.87	3.94
10	R	2.25	2.00	4.25	2.19	2.06	4.25	2.13	2.06	4.19
	L	2.38	1.87	4.25	2.25	1.88	4.19	2.13	2.12	4.25
11	R	2.25	1.87	4.13	2.19	1.88	4.06	2.13	2.00	4.13
	L	2.31	1.87	4.19	2.25	1.88	4.13	2.19	2.00	4.19
12	R	2.06	2.00	4.06	2.00	1.94	3.94	1.94	2.00	3.94
	L	2.19	1.94	4.13	2.19	1.88	4.06	2.06	1.94	4.00
13	R	1.88	2.06	3.94	1.81	2.06	3.87	2.00	1.94	3.94
	L	1.94	2.00	3.94	1.94	2.00	3.94	2.00	2.06	4.06
14	R	2.25	1.94	4.19	2.13	2.00	4.13	2.00	2.00	4.00
	L	2.06	2.00	4.06	2.00	2.06	4.06	2.13	1.94	4.06
15	R	2.19	1.88	4.06	2.13	1.88	4.00	2.19	1.94	4.13
	L	2.19	1.88	4.06	2.13	1.94	4.06	2.25	1.94	4.19
16	R	2.38	1.87	4.25	2.31	1.94	4.25	2.25	2.06	4.31
	L	2.38	1.94	4.25	2.38	1.94	4.31	2.25	2.00	4.25
17	R	2.31	2.06	4.38	2.25	2.13	4.38	-	1.94	-
	L	2.31	2.06	4.38	2.25	2.13	4.38	2.25	1.94	4.19
18	R	2.25	1.87	4.13	2.19	1.94	4.13	2.13	2.00	4.13
	L	2.25	1.87	4.13	2.25	1.94	4.19	2.13	2.06	4.19
19	R	2.13	2.06	4.19	2.19	2.00	4.19	1.94	2.12	4.06
	L	2.19	2.00	4.19	2.19	2.06	4.25	1.94	2.12	4.06
20	R	1.94	2.12	4.06	1.94	2.12	4.06	-	1.94	-
	L	2.06	2.00	4.06	2.00	2.06	4.06	2.25	1.94	4.19

APPENDIX F

ABR Interaural Latency Difference Raw Data

	90 dB nHL		80 dB nHL		70 dB nHL	
SUBJ	**Wave V**	**IPL I-V**	**Wave V**	**IPL I-V**	**Wave V**	**IPL I-V**
1	0.06	0.06	0.06	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.06	0.00	0.06	0.06	0.06
4	0.12	0.07	0.12	0.07	0.13	0.07
5	0.00	0.00	0.00	0.00	0.06	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.07	0.00	0.00	0.00
8	0.00	0.00	0.00	0.06	0.07	0.06
9	0.00	0.00	0.00	0.00	0.00	0.00
10	0.06	0.00	0.00	0.06	0.07	0.06
11	0.06	0.06	0.06	0.06	0.07	0.06
12	0.06	0.07	0.07	0.00	0.00	0.00
13	0.06	0.00	0.13	0.06	0.12	0.06
14	0.00	0.13	0.00	0.12	0.06	0.12
15	0.00	0.00	0.06	0.06	0.00	0.06
16	0.06	0.06	0.00	0.06	0.00	0.06
17	0.00	0.00	0.00	0.06	0.00	0.06
18	0.00	0.00	0.06	--	0.00	--
19	0.00	0.00	0.06	0.06	0.13	0.06
20	0.00	0.00	0.00	0.00	0.00	0.00

APPENDIX G

ABR Amplitude Measurements Raw Data

		90 dB nHL			80 dB nHL			70 dB nHL		
SUBJ	**EAR**	**W I-I'**	**W V-V'**	**W V/I Ratio**	**W I-I'**	**W V-V'**	**W V/I Ratio**	**W I-I'**	**W V-V'**	**W V/I Ratio**
1	R	0.67	0.44	0.66	0.55	0.44	0.80	0.51	1.96	0.38
	L	0.59	0.36	0.61	0.56	0.32	0.57	0.36	0.40	1.11
2	R	0.75	1.09	1.45	0.50	0.89	1.78	0.36	0.80	2.22
	L	0.53	1.17	2.21	0.58	0.84	1.45	0.41	0.74	1.80
3	R	0.29	0.90	3.10	0.40	0.72	1.80	0.30	0.48	1.60
	L	0.51	0.92	1.80	0.43	0.82	1.91	0.20	0.58	3.22
4	R	0.41	0.94	2.92	0.37	0.74	2.00	0.36	0.49	1.36
	L	0.40	0.92	2.30	0.38	0.70	1.84	0.32	0.55	1.77
5	R	0.32	0.60	1.88	0.32	0.54	0.69	0.28	0.43	1.54
	L	0.31	0.54	1.74	0.45	0.57	1.27	0.26	0.46	1.77
6	R	0.36	0.44	1.22	0.51	0.34	0.67	0.18	0.39	2.17
	L	0.47	0.45	0.96	0.42	0.41	0.98	0.31	0.29	0.94
7	R	1.05	1.00	0.95	1.08	0.59	0.55	0.77	0.50	0.65
	L	0.86	0.63	0.73	0.82	0.57	0.70	0.50	0.43	0.86
8	R	0.77	0.29	0.38	0.54	0.26	0.48	0.20	0.18	0.90
	L	0.72	0.33	0.46	0.52	0.27	0.52	0.21	0.19	0.90
9	R	0.47	0.64	1.36	0.39	0.32	0.82	0.34	0.26	0.76
	L	0.60	0.38	0.63	0.45	0.33	0.73	0.29	0.37	1.28
10	R	0.47	0.75	1.60	0.48	0.40	0.83	0.25	0.20	0.80
	L	0.46	0.84	1.83	0.35	0.43	1.23	0.24	0.19	0.79
11	R	0.44	0.69	1.57	0.38	0.32	0.84	0.23	0.31	1.35
	L	0.27	0.42	1.56	0.41	0.38	0.93	0.20	0.32	1.60
12	R	0.59	0.36	0.61	0.39	0.38	0.97	0.30	0.25	0.83
	L	0.48	0.52	1.08	0.43	0.46	1.07	0.28	0.48	1.75
13	R	0.53	0.46	0.87	0.41	0.50	1.22	0.32	0.33	1.03
	L	0.53	0.46	0.87	0.40	0.45	0.89	0.39	0.25	0.64
14	R	0.87	0.79	0.91	0.69	0.51	0.74	0.44	0.49	1.11
	L	0.58	0.56	0.97	0.70	0.54	0.77	0.53	0.36	0.68
15	R	0.32	0.37	1.16	0.34	0.24	0.71	0.23	0.25	1.09
	L	0.25	0.41	1.64	0.34	0.30	0.88	0.30	0.21	0.70
16	R	0.74	0.84	1.14	0.63	0.57	0.90	0.30	0.50	1.67
	L	0.46	0.70	1.52	0.59	0.53	0.90	0.38	0.55	1.45
17	R	0.46	0.57	1.24	0.48	0.47	0.98	0.33	0.34	1.03
	L	0.41	0.52	1.27	0.52	0.43	0.83	0.33	0.34	1.03
18	R	0.26	0.52	2.00	0.19	0.48	2.53	--	0.48	--
	L	0.28	0.47	1.68	0.31	0.41	1.32	0.19	0.52	2.74
19	R	0.48	0.56	1.17	0.40	0.53	1.33	0.34	0.54	1.59
	L	0.48	0.66	1.38	0.39	0.60	1.54	0.30	0.43	1.43
20	R	0.54	0.54	1.00	0.48	0.29	0.60	0.17	0.40	2.35
	L	0.53	0.47	0.89	0.47	0.39	0.83	0.24	0.58	2.42

APPENDIX H

Increased Click Rate (Wave V Absolute Latency)

Raw Data

SUBJ	EAR	61.1/sec	19.1/sec	Rate Shift
1	R	5.95	5.51	0.44
	L	5.95	5.57	0.38
2	R	5.89	5.57	0.32
	L	5.95	5.57	0.38
3	R	5.89	5.45	0.44
	L	5.76	5.45	0.31
4	R	6.01	5.64	0.37
	L	6.14	5.76	0.38
5	R	5.70	5.32	0.38
	L	5.76	5.32	0.44
6	R	6.01	5.82	0.19
	L	6.01	5.82	0.19
7	R	6.01	5.51	0.50
	L	6.01	5.51	0.50
8	R	6.01	5.64	0.37
	L	6.01	5.64	0.37
9	R	6.01	5.51	0.50
	L	6.07	5.51	0.56
10	R	6.01	5.70	0.31
	L	5.95	5.64	0.31
11	R	6.01	5.64	0.37
	L	6.14	5.70	0.44
12	R	5.82	5.51	0.31
	L	5.89	5.57	0.32
13	R	5.95	5.45	0.50
	L	6.07	5.51	0.56
14	R	5.82	5.57	0.25
	L	5.89	5.57	0.32
15	R	6.07	5.70	0.37
	L	6.07	5.70	0.37
16	R	6.07	5.64	0.43
	L	6.07	5.70	0.37
17	R	6.26	5.82	0.44
	L	6.20	5.82	0.38
18	R	6.07	5.64	0.43
	L	6.07	5.64	0.43
19	R	6.07	5.70	0.37
	L	6.07	5.70	0.37
20	R	5.95	5.57	0.38
	L	5.95	5.57	0.38

APPENDIX I

Towson University Hearing and Balance Clinic

ABR Normative Data for Bio-logic Equipment

Patient Name: _____ DOB: _____ Date: _____

ABR Normative Data for Latency Measurements

Absolute Latency (ms)	**90 dB nHL** **Mean** SD (+/- 2.5)	**80 dB nHL** **Mean** SD (+/- 2.5)	**70 dB nHL** **Mean** SD (+/- 2.5)	**Right Ear** ___dB nHL	**Left Ear** ___ dB nHL	**Right Ear** ___ dB nHL	**Left Ear** ___ dB nHL
Wave I	**1.49** (1.27-1.72)	**1.57** (1.32-1.82)	**1.69** (1.49-1.89)				
Wave III	**3.63** (2.85-4.41)	**3.73** (3.38-4.08)	**3.80** (3.50-4.10)				
Wave V	**5.60** (5.30-5.90)	**5.69** (5.39-5.99)	**5.78** (5.53-6.03)				
Interpeak Latency (ms)	**90 dB nHL** **Mean** SD (+/- 2.5)	**80 dB nHL** **Mean** SD (+/- 2.5)	**70 dB nHL** **Mean** SD (+/- 2.5)	**Right Ear** ___ dB nHL	**Left Ear** ___dB nHL	**Right Ear** ___dB nHL	**Left Ear** ___dB nHL
Waves I-III	**2.19** (1.79-2.59)	**2.16** (1.76-2.56)	**2.10** (1.80-2.40)				
Waves III-V	**1.93** (1.74-2.19)	**1.96** (1.71-2.21)	**1.99** (1.69-2.29)				
Waves I-V	**4.12** (3.75-4.50)	**4.12** (3.75-4.50)	**4.09** (3.79-4.39)				

Interaural Latency Differences

Interaural latency differences for wave V and for IPL I-V should be < 0.2 ms.

Wave V ___ dB nHL	**Wave V** ___dB nHL	**IPL I-V** ___dB nHL	**IPL I-V** ___ dB nHL

Wave V/I Amplitude Ratio

Wave V/I amplitude ratio should be > .05 µV.

Right Ear ___dB nHL ___dB nHL		**Left Ear** ___dB nHL ___dB nHL	

Rate Differences

Wave V absolute latency should shift 0.1 ms for every 10 fold increase in click rate. (Picton, Stapells, & Campbell, 1981).

90 dB nHL	**19.1/sec Wave V**	**61.1/sec Wave V**	**Wave V Shift**
Right			
Left	.		

Stimulus Polarity

Right ear - ABR polarity inversion in response to condensation click stimulus

Left ear – ABR polarity inversion in response to condensation click stimulus

No	**Yes**

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QUALIFICATIONS and GOALS PROFILE

Au.D. candidate at an ASHA-accredited University. Thrives in a team-oriented environment. Has excellent interpersonal skills with patients, supervisors, and peers alike. Always driven to provide the best patient care possible, all while learning and growing as a student clinician.

EDUCATION

Present Doctor of Audiology: Anticipated Graduation - May, 2017
Towson University, Towson, MD
GPA: 3.69

Thesis: The Auditory Brainstem Response (ABR):
A Collection Of Normative Data Using The Bio-logic AEP System

2013 Bachelor of Science in Speech Language Pathology and Audiology
Towson University, Towson, MD
GPA: 3.63

SKILLS

Educational background in American Sign Language, basic proficiency
Familiar with NOAH software

PRACTICUM EXPERIENCE

Spring ’16 ***Christiana Care Hospital,*** Newark, DE
Population: *adult, geriatric, pediatric*
Skills exercised:

- Complete audiological evaluations
- Distortion product optoacoustic emissions
- Pediatric audiological evaluations: *Visual Reinforcement Audiometry (team)*
- Cochlear implant evaluations and mappings: *Med-El, Cochlear*

- Hearing aid evaluations, fittings, and checks: *Resound, Oticon*
- Electrophysiology: *Cervical Vestibular Evoked Myogenic Potential, Electrocochleography*
- Balance/Vestibular assessment: *Electronystagmography, Posturography*
- Counseling of patients

Fall ‘15 ***Gehris, Jordan, Day and Associates, LLC***, Bel Air, Towson, and Baltimore, MD

Population: *adult, geriatric, pediatric*

Skills exercised:

- Complete audiological evaluations
- Pediatric audiological evaluations: *Visual Reinforcement Audiometry (solo)*
- Hearing aid evaluations, fittings, and checks: *Resound, Oticon*
- Electrophysiology: *Auditory Brainstem Response, Electrocochleography*
- Balance/Vestibular assessment: *Videonystagmography*
- Counseling of patients

Summer ‘15 ***ENTAA Care***, Annapolis, Laurel, and Kent Island, MD

Population: *adult, geriatric, pediatric*

Skills exercised:

- Complete audiological evaluations
- Limited otoacoustic emissions
- Hearing aid evaluations, fittings, and checks: *Unitron, Phonak*
- Counseling of patients

Spring ’15 ***White Oak Assessment Center (Child Find)***, Parkville, MD

Population: *pediatric*

Skills exercised:

- Pediatric audiological evaluations: *Visual Reinforcement Audiometry, Conditioned Play Audiometry (team)*
- Fitting and troubleshooting FM systems: *Phonak Inspiro, Rodger*
- Troubleshooting hearing aids
- Attend Individualized Educational Plan (IEP) meetings

Spring ’13 to Fall ’14 ***Towson University Balance and Hearing Center,*** Towson, MD
Population: *adult, geriatric*
Skills exercised:

- Complete audiological evaluations
- Limited otoacoustic emissions
- Hearing aid evaluations, fittings, and checks: *Phonak, Rexton, limited Oticon*
- Real ear measurements: *Speech Mapping*
- Counseling of patients

MEMBERSHIPS

2014-2015 Media Committee of the National Student Academy of Audiology, member

- *Delegated article assignments to fellow members for SAAy Anything e-newsletter*
- *Collected and assisted in preparing articles for publication*
- *Conducted PhD spotlight interviews*

2013- Present National Student Academy of Audiology, member
2013- Present Student Academy of Audiology, Towson University Chapter, member

- *Took part in philanthropic events (St. Jude’s Walk, LAPS for Autism Walk)*
- *Fundraised for Towson University’s Chapter*

SERVICE

2015 Noise Monitoring at Towson University Concert
2015 Special Olympics: Healthy Hearing, volunteer
2014 Maryland Academy of Audiology Convention, volunteer