TOWSON UNIVERSITY
OFFICE OF GRADUATE STUDIES

BONE CONDUCTION EQUAL-LOUDNESS CONTOURS: PLACEMENT, FREQUENCY, AND INTENSITY

By

Jennifer Lasman

A doctoral thesis

Presented to the faculty of

Towson University

In partial fulfillment

Of the requirements for the degree

Doctor of Audiology

Department of Audiology, Speech-Language Pathology and Deaf Studies

Towson University
Towson, Maryland 21252

May, 2015

Towson University
Office of Graduate Studies

Thesis Approval Page

This is to certify that the thesis prepared by Jennifer Lasman entitled Bone Conduction Equal Loudness Contours: Placement, Frequency, and Intensity has been approved by the thesis committee as satisfactorily completing the thesis requirements for the degree of Doctor of Audiology.

Thesis Chairperson: Diana C. Emanuel, Ph.D.	06/09/14 Date
Committee Member: Tomasz Letowski, Ph.D.	5/17/14 Date
Committee Member: Kimberly A. Pollard, Ph.D.	5/12/14 Date
Dean of Graduate Studies Janet Delany, Ph.D.	6/10/14 Date

Acknowledgements

I would like to thank my committee members, Dr. Diana Emanuel, Dr. Tomasz Letowski, and Dr. Kimberly Pollard for mentoring me throughout this process. Without your patience, this would have never been accomplished.

To my friends and family, thank you for being there for me when I was stressed and always taking those three a.m. phone calls.

Abstract

Bone Conduction Equal Loudness contours: Frequency, Placement, and Intensity

Jennifer Lasman

Bone conduction communication is supplemental to air conduction in normal hearing individuals; however, bone conduction devices have advantages compared to air conduction devices in certain circumstances. Air conduction devices such as headphones require the open ear canal to be covered, which causes attenuation of surrounding environmental sounds. With a bone conduction device, the ear canal can be left open allowing the signal to be transmitted without affecting awareness of surrounding noise, which is required for military communication and optimal for recreational communication purposes. However, additional research is needed to optimize the use of bone conduction communication devices. This study was conducted to develop bone conduction equal-loudness contours at mastoid and condyle placements. A portion of these results were compared to existing and well-established air conduction contours, while bone conduction contours were unique to this study. Thirty participants (15 males and 15 females) were trained to compare the loudness of two narrow band noise stimuli and three types of comparisons were made: soundfield to soundfield, soundfield to bone conduction, and bone conduction to bone conduction. This study had 3 goals: (1) to establish equal loudness contours for sound field stimuli and compare these to data previously published, (2) to compare sound field to bone conduction loudness levels at the same frequencies to compare loudness judgments across modality, and (3) to establish bone conduction loudness contours with unilateral and bilateral application in mastoid and condyle locations. Data analysis was conducted using repeated measures ANOVA, dependent t-tests and paired sample t-tests. Results indicated that condition, placement, and intensity were not statistically significant between the bone conduction equal loudness contours at 20 and 40 dB HL. Frequency was significant in each bone conduction equal loudness contour at 20 and 40 dB HL. Paired sample t-tests were conducted to examine differences with the current study's soundfield-to-bone data. Results showed that statistically significant differences were present at 250 and 1000 Hz. Dependent t-tests were conducted to compare the published ISO 2003 values to the current study's soundfield values at 40 dB HL. Results indicated that there were no statistically significant differences between the curves.

Table of Contents

Page

List of Tables

List of Figures

Chapter 1

Introduction

Bone conduction research has been conducted for many years in the areas of diagnostic testing, treatment for hearing loss, and recreational and military communication devices. Clinically, bone conduction is primarily used to distinguish between a conductive or sensorineural hearing loss. Bone conduction testing is very sensitive to test conditions, as the bone oscillator placement and amount of static force applied to the oscillator can alter threshold results. If a conductive hearing loss is confirmed, the treatment would be a bone conduction hearing aid, which transmits the signal by vibrating the bones of the skull. Bone conduction communication is supplemental to air conduction in normal hearing individuals; however, bone conduction devices have advantages compared to air conduction devices in certain circumstances. Air conduction devices such as headphones require the open ear canal to be covered, which causes attenuation of surrounding environmental sounds. With a bone conduction device, the ear canal can be left open allowing the signal to be transmitted without affecting awareness of surrounding noise, which is required for military and recreational communication purposes. However, additional research is needed to optimize the use of bone conduction communication devices. In this study, bone conduction equal-loudness contours are examined in order to compare loudness perception within bone conduction paradigms (unilateral, bilateral; mastoid, condyle) and across bone and sound field delivery systems. The purpose of the study was to develop BC equal-loudness contours that can be compared to existing and well-established AC contours. The long term goal of this research was to improve military and recreational communication using bone conduction devices.

Chapter 2

Literature Review

Air and Bone Conduction

There are two mechanisms through which a person can hear: air conduction and bone conduction. The air conduction pathway is the primary method of energy transfer from sound in the environment to the cochlea, where neural activity begins. Air conduction transmission occurs when sound is channeled by the pinna of the outer ear to the ear canal and middle ear and to the cochlea of the inner ear. Any amount of external force or sound pressure will cause the skull to vibrate. However, for a given sound pressure, the ear response to air conducted sound is about 50 dB SPL stronger than it is to bone conducted sound. Bone conducted sounds will cause the bones of the skull to vibrate, resulting in the direct vibration of fluid within the cochlea, which happens simultaneously but separately to the sound wave transmission through the air conduction pathway (Emanuel & Letowski, 2009). Bone conduction may also occur with direct vibration of the skull, without air conduction transmission. The air conduction pathway is by far the more effective pathway of sound transmission for airborne sounds, compared to bone conduction, and the bone conduction pathway needs direct stimulation of the bones of the skull (e.g., when a vibrating force is applied to the skull) for it to be effective (Henry & Letowski, 2007). The presence of the bone conduction mechanism is clearly evident when people hear their own voices as they speak. When speaking, a person hears his or her own voice through the air conduction pathway when the sound that comes from their mouth arrives at their ears; however, a person also hears his or her own voice as it is transmitted through the bones of the skull to the cochlea, and the contribution of this pathway results in a different filtering of sound, and thus in a difference in the sound quality in comparison to hearing a recording of one's voice (Brandt, Hakansson, & Stenfelt, 2006). However, listening and communicating by bone conduction is beneficial in a limited number of circumstances compared to air conduction and can be used as a supplement to the air conduction pathway, or if the normal air conduction pathway is not working.

Skull Vibrations

The human skull is a bony structure consisting of cranial and facial bones that are surrounded by tissue and fluid in the living body. The skull vibrates through the inertial or compression mode during bone conduction transmission of sound. In the inertial mode, the entire skull vibrates together in the same direction; in compression mode, however, portions of the skull vibrate in different directions relative to each another. The mode of skull vibration depends on the frequency of the signal. When there is a low frequency signal (defined by Bekesy as 200 Hz or lower), the skull will vibrate in the inertial mode; in contrast, when there is a high frequency signal (defined by Bekesy as 1500 Hz or higher), the skull will vibrate in the compression mode (Littler, Knight, & Strange, 1952). When sound energy is applied directly onto the skull it causes the sound to be transferred much more efficiently compared to sound waves hitting the skull from the air. When the sound source is directly on the skull it better matches impedance of the skull than surrounding air, which results in more efficient transmission of the sound (Toll, Emanuel, & Letowski, 2011).

Clinical Origins

As previously discussed, bone conduction is the transmission of sound directly to the cochlea of the inner ear via the bones of the skull, bypassing the air conduction pathway of the outer and middle ear (Stenfelt & Hakansson, 2001). The earliest bone conduction observations date back to the Renaissance Era when Girolamo Cardano discovered that biting on a rod, connected to a sound source, resulted in the direct transfer of sound to his ear (Mudry & Tjellstrom, 2011). A few years later, Hieronymus Capivacci, a physician in northern Italy, applied the observations of Cardano and developed the first documented clinical test of bone conduction (Feldmann, 1997). For this clinical test, an iron rod was connected to a patient's teeth on one end and to a musical string instrument called a zither on the other. If the instrument was played and the patient heard the sound, it was thought that the hearing disorder originated from the tympanic membrane. If the patient did not hear music from the instrument, it was concluded that there was pathology of the auditory nerve. Although the differential diagnosis was limited to only two parts of the auditory system, thus not clinically accurate by today's standards, this was the first recorded attempt to use bone conduction testing to distinguish between sensorineural and conductive hearing loss. Later, in 1711, the tuning fork was invented. Its initial purpose was for musical instrument tuning; however, in 1845 Schmalz described the use of the tuning fork for the Weber test (Feldmann, 1997; Thiagarajan, 2012). The Weber test was used as a hearing screener to differentiate between a unilateral conductive or sensorineural hearing loss. If the patient heard the sound better in the ear that was affected, then the hearing loss was conductive; if it was heard better in the ear that was unaffected then it was a sensorineural hearing loss (Yueh, Shapiro, MacLean & Shekelle, 2003). The tuning fork was so useful for differential diagnosis of conductive versus sensorineural hearing loss that it still has medical uses, even today (Yueh, Shapiro, MacLean & Shekelle, 2003).

Musical Origins

Ludwig Van Beethoven (1770-1827) used bone conduction to compose some of his most famous works. Beethoven first developed tinnitus and hearing loss at the age of 26, but it was not until age 44 that he became severely hearing impaired and developed severe tinnitus. At that time, he decided he would only compose music, and subsequently shied away from live musical performance (Marek, 1969). In order to continue composing, he used bone conduction to listen to his music, by biting on a rod and attaching it to the soundboard plate on the piano (Henry & Letowski, 2007). This allowed the vibrations to transfer from the piano to his jaw, which increased his perception of the sound. The vibrations from the piano traveled through the bones of his skull to stimulate the cochlea, thus allowing Beethoven to hear the music via bone conduction, even though he was not able to hear through the conventional air conduction pathway (Marek, 1969). Other methods he used to perceive the music were cutting off the legs of the piano so that the vibrations could travel through the floorboards and, as a result, Beethoven was able to feel the vibrations through his body (Maxwell, 2011). Despite not being able to hear the music via air conduction after he became deaf, Beethoven used his hearing through bone conduction to compose some of his most well-known symphonies such as "Moonlight Sonata", "Fidelio", and his 9th symphony "Ode to Joy."

Bone Conduction Hearing Aid Origins

In 1876, the first bone conduction hearing aid, known as the Fonifero, was invented (Banga, Lawrence, Reid, & McDermott, 2011). The Fonifero (as cited in Banga et al., 2011), was a metal device with a rod on one end that was worn around the speaker's neck. The other end was held between the listener's teeth or against the mastoid. Three years later, Rhodes (1879, as cited in Berger, 1976) created the Audiphone as an alternate device to deliver sound via bone conduction. The Audiphone consisted of a sheet of vulcanite molded into a fan shape by adjustable chords. This fan was held between the listener's teeth. The fan collected and then transferred sound to the listener's cochlea. As listeners held the fan between their teeth, they used the adjustable cords to provide tension to the fan, resulting in better vibration of the sound (Berger, 1976). Over a century later in the 1980s, Xomed developed the first surgically implanted bone conduction hearing aid. This invention was followed by the invention of the Audiant, the first bone conduction transcutaneous device; however, the Audiant is no longer used (Henry & Letowski, 2007). All of these early inventions and techniques of bone conduction provided the foundation for current bone conduction testing techniques used for differential diagnosis and bone conduction devices to treat some forms of hearing loss.

Current Bone Conduction Hearing Devices

Air conduction hearing aids are most commonly used to reduce the effects of hearing loss; however, for conductive and some mixed hearing losses, a bone conduction device is used. These devices can be applied with a removable headband or may be implanted. Implanted bone conduction devices have become an increasingly popular alternative to air conduction hearing aids (Mylanus, Van der Pouw, Snik, & Cremers, 1998). The bone-anchored hearing aid (BAHA) is one of several bone-conduction implants (BCIs). The BAHA, developed in Sweden, was first introduced in 1980s. The BAHA is a percutaneous device and consists of three components: a titanium implant inserted into the mastoid bone behind the ear, an outer abutment attached to the implant, and a hearing processor connected to the abutment (Christensen, Smith-Olinde, Kimberlain, Richter, & Dornhoffer, 2010). The sound pathway begins at the processor, where it receives the sound and converts it to a vibratory signal. The abutment acts as a bridge, transferring vibrations between processor and implant. At the implant, the vibrations shake the bones of the skull and therefore stimulate the cochlea (Brandt et al., 2006). Since the introduction of the BAHA, more than 40,000 patients have been implanted (Cochlear annual report, 2008).

A non-invasive alternative to the BAHA is the more traditional, external bone conduction headband device. A vibrator is attached to a headband that sits on the mastoid. The listener wears a hearing aid that serves to receive sounds that surround the listener and sends them to the vibrator (Henry & Letowski, 2007). Another modern non-surgical type of bone conduction hearing aid is the SoundBite; the vibration portion of this product is positioned in the mouth instead of on the mastoid. It is most often used by patients with unilateral deafness or a conductive hearing loss (Popelka, 2010). The SoundBite is comprised of a personal mouthpiece and a behind-the-ear (BTE) microphone. The signal travels from the microphone to the mouthpiece, which sends the signal through the teeth. These bone vibrations will stimulate the bones of the skull and the cochlea (Popelka, 2010). “The teeth are well suited for transmission of bone conducted sound and have a sensitivity close to that of the skin covered mastoid; both of these, however, are less sensitive than a percutaneous approach at the mastoid for frequencies above 1000 Hz" (Stenfelt, 1999).

Bone Conduction in Clinical Audiometry

The first bone conduction tests used diagnostically were tuning fork tests (Thiagarajan, 2012). Tuning fork tests are used by medical personnel to evaluate a person's hearing acuity with the placement of the vibrating fork on several different areas on the head, such as the forehead, chin, or mastoid of the patient. The placement of the tuning fork varies based on the test performed. While useful, tuning fork tests are not able to indicate the degree of hearing loss like air and bone conduction audiometry, but instead lateralize to the ear that is affected. Furthermore, even though multiple frequency tuning forks can be used, the frequency specific information from these tests is limited. In audiometric bone conduction testing, the vibrator is placed on one mastoid (direct stimulation to the skull bone) or on the forehead; however, the signal is transmitted to both cochleae, regardless of placement location, because of low transcranial attenuation (Stenfelt, 2011). Some of the transmission is attenuated by the skin layer between the vibrator and the skull, although at low frequencies this attenuation is not very effective. It has been found that at the higher frequencies (greater than 1,000 Hz), the skin layer attenuation is as great as 5-15 dB (Brandt, Håkansson, & Stenfelt, 2006).

When testing a person's threshold for bone conduction, the amount of static force of the headband needs to be considered (Henry & Letowski, 2007). According to the American National Standards Institute (ANSI), the recommended force used in clinical audiometry when testing patients is 550 gf ± 50 gf (ANSI, 2004) because this force is capable of transferring the signal through the skin to reach the cochlea regardless of the frequency of stimulation. However, such a large force may cause physical pain to the listener and several studies have indicated valid audiometric testing can be obtained with a lower force level with greater comfort to listeners (Toll, Emanuel & Letowski, 2011). Standards for air conduction headsets are similar in that there is an expectation for the force level against the head, as this can affect testing. Audiometric testing includes a comparison of air conduction thresholds to the bone conduction thresholds to indicate if an air-bone gap is present. The presence of an air-bone gap indicates a conductive hearing loss (Henry & Letowski, 2007).

Placement of the Transducer

The forces of the vibrator, as well as the transducer location, are important facets to the transmission of a clear, undistorted signal (Henry & Letowski, 2007). The closer the bone conduction vibrator is to the cochlea, the better the stimulation of the cochlea; the farther away the vibrator is from the cochlea, the greater the force required for perception (Stenfelt et al., 2000). Although the vibrator may be placed on the mastoid or forehead, mastoid placement is closer to the cochlea, as the temporal bone surrounds the cochlea. Mastoid placement is generally preferred over a forehead placement because mastoid placement utilizes the ossicular chain, whereas forehead placement bypasses the ossicular chain (Henry & Letowski, 2007). It has been shown that the ossicular chain introduces an additional input (middle ear inertial component) to the transmitted signal. In addition, the mastoid placement of a bone vibrator results in better thresholds than forehead placement by 10-12 dB (Henry & Letowski, 2007). In contrast, bone conduction for communication is rarely placed on the forehead or the mastoid (Stenfelt et al., 2000).

A study conducted by McBride, Letowski, and Tran (2008) suggested that condyle placement is better than mastoid placement for communication purposes. The condyle operates in the direction of the ossicular chain movement and is close enough to the cochlea to still transmit a strong signal via bone conduction.

Commercial Applications of Bone Conduction

Bone conduction is most widely used as a diagnostic tool and in hearing aid products. However, there are many commercial uses for bone conduction including music and communication technology (Henry & Letowski, 2007). Some of the current products that use bone conduction are the Aftershokz bone conduction headset, the SwimMP3, the Amphicom interactive underwater trails, and the Aqua FM Pro (Amphicom, 2003; “SwiMP3 2G”, 2012). Instead of sitting on top of the ear canal opening like conventional supra aural headphones, the Aftershokz sits right in front of the ear and transmit the signal through the cheekbones. This allows joggers, bike riders, roller bladders etc. to be able to listen to music while simultaneously exercising safety with the ability to hear cars horns or any verbal warnings to their safety compared to over the ear supra-aural headphones. Bone conduction headphones also reduce the risk of eardrum damage (pain and perforations) from excessively loud music for long periods of time, as sound is not impinging on the ear drum ("Aftershokz open ear," 2013). However, they do not eliminate the threat of noise induced hearing loss. The force the transducer exerts on the cheekbones needs to be sufficient to transmit signals with good fidelity. However, the force should not be too strong or the wearer will start to feel low frequencies (250,500 Hz) instead of hearing them, which means it is not processed in the auditory cortex. Additionally, the pressure may cause discomfort. The Aftershokz entertainment/communication products not only allow hands-free operation, but also allow the person to simultaneously use bone conduction stimulation as well as be aware of their surrounding environment. (“Aftershokz open ear, 2013”; Amphicom, 2003; “SwiMP3 2G”, 2012)

Bone conduction also plays an important role in military communications. During warfare, bone conduction headsets allow military personnel to communicate with team members while keeping the open ear canal alert to environmental sounds. One headset model consists of two vibrators resting against the right and left temples and a microphone placed near the mouth to pick up the speech signal (Henry & Letowski, 2007). This allows the user to be virtually silent as the microphone can pick up a whisper and the vibrator is practically noiseless (Herstens, 2012). In addition, bone conduction microphones can be used for military and recreational communication. The microphone sits in the external auditory canal receiving both air and bone conduction signals. The bone conduction and air conduction signals are then transformed into an electrical signal. This electrical signal has any noise in the signal removed through a filtration system and the pure speech signal is received via a wireless receiver. However, this technology is known to have possible distortion making it difficult for the signal to be heard (Boesen, 2000).

One potential limitation of bone conduction technology in military or security operations is that some of the signal may be leaked and therefore heard by people other than the user. This most often happens when the bone vibrator has a large area of contact causing a greater intensity level. This is also a characteristic of earphones; however, for military purposes, this leakage of sound risks private conversations being heard, which may compromise the safety of the soldier (Henry & Letowski, 2007).

The SwimMP3 is used mostly by swimmers; it provides music through bone conduction under water. The MP3 player connects to the swimmer's goggles and puts pressure on the cheekbones. The vibration of the cheekbones is transmitted to the rest of the skull, thereby stimulating the cochlea and allowing the music from the flash drive to be transmitted and processed ("SwiMP3 2G"). The Amphicom is also used under water, but with devices shaped like BC headphones. Each buoy in the trail contains an underwater FM transmitter, which transmits a pre-recorded tour of the underwater dive site to SCUBA divers wearing bone conduction headphones. The Aqua FM Pro uses a mouthpiece to communicate with the swimmer or snorkeler. The snorkel has a built in radio receiver and the swimmer receives the sound through an active mouthpiece that uses bone conduction through the teeth. It also allows a swim instructor to be outside on land, and still be able to communicate with student swimmers during a lesson, as the instructor can wear a headphone and microphone (Amphicom, 2003).

A bone conduction device aimed towards children is a toothbrush called Tooth Tunes, developed by Hasbro, Inc. It is a toothbrush that emits fun tunes to the user through the teeth to the inner ear. The toothbrush plays a song for two minutes, which encourages children to brush their teeth for as long as the song is playing (Elliott, 2007).

Statement of Purpose

Bone conduction technology has been studied as a mode of communication for the past decade; however, bone conduction equal loudness contours have not been established. Bone anchored hearing aids, military communication devices, and recreational devices are some examples of bone conduction devices. Some of the advantages of communication through bone conduction are noted to be unobstructed ears, low leakage of sound, and no interference with hearing protection devices. The variety of skull placements for the bone vibrator allows the communication device to be worn with protective gear and enhance comfort of the user (Pollard et al., 2013). Because of the importance of optimal communication for bone anchored hearing aids, military purposes, etc. an extensive body of knowledge regarding bone conduction transmission, including loudness perception, must be generated. Therefore, the purpose of this study was to examine loudness contours for bone conduction in a sample of individuals for whom some information about bone to soundfield and soundfield loudness contours was also collected. Specifically, the purpose of this study was to establish the equal loudness contours for:

1. Bone-to-bone at 250, 500, 1000, 2000, 3000, 4000, and 6000 Hz at 20dB HL and 40 dB HL for two different skull placements and conditions,
2. Soundfield-to-soundfield at 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz at 40 dB HL,
3. Soundfield-to-bone at 250, 500, 1000, 2000, 3000, 4000, and 6000 Hz at 40 dB HL with the bone vibrator on the right mastoid.

This thesis is based on a dataset collected collaboratively by three doctoral students, merged, and then used in the aggregate by all three students to answer different research questions. In this study, each of the three doctoral students was responsible for a specific area of analysis yielding three unique thesis projects. Study one, described by Arvindekar (2015), focused on equal loudness contours and previous studies that have yielded some results relevant to bone conduction equal loudness contours. Study two, written by Andreaggi (2015), focused on laterality, subject variability, and the differences between the unilateral and bilateral conditions. Study three, described in this thesis (Lasman), focused on soundfield-to-bone equivalent loudness levels, intensity differences and mastoid versus condyle perception of bone conduction. Per the direction of the thesis committee, considering the group nature of this project, the methods, statement of purpose, and the results section were co-authored by Jennifer Lasman, Sanghmitra Arvindekar, and Dave Andreaggi and are identical. All other thesis sections are the original work of the author of this thesis.

Chapter 3

Methods

Institutional Review Board (IRB) for the protection of human subjects permission was obtained for this study (See appendix A). The statement of purpose, methodology, and results were prepared as a group effort by Jennifer Lasman, Sanghmitra Arvindekar, and David Andreaggi. Three separate types of analyses were conducted individually by the three researchers to answer their unique study questions. All other written portions of this thesis are the individual work of Jennifer Lasman. The focus of the Lasman (2015) study was to determine bone-to-soundfield equivalent levels, to examine intensity differences and to examine mastoid versus condyle perception of bone conduction.

Participants

A group of 30 otologically normal participants (14 women and 16 men), aged 18 to 30 years, with normal hearing sensitivity were recruited, via posted fliers and personal contact, to participate in the study. A small incentive (e.g. movie coupons, candy) was offered to encourage participation. Prior to participation in the study, each participant had a hearing screening. All participants had normal hearing thresholds (≤15 dB HL at 500, 1000, 2000 and 4000 Hz). Participants also had normal tympanometric results based on standard tympanometric screening procedures (Jerger, Anthony, Jerger, & Mauldin, 1974). The 30 participants consisted of three groups of 10 participants, each tested by one of the three researchers involved in this study. Data were aggregated across all 30 participants for the purposes of all statistical analyses. However, each of the three doctoral students was responsible for a specific area of analysis yielding three unique thesis projects.

Equipment

Tympanometry was screened using a GSI-38 tympanometer. A two-channel Astera audiometer was used to present pure tone stimuli for the hearing screening and the experiment. Channel 1 was used to present the reference signal and Channel 2 to present the test signal. All sound stimuli were played from a Sony Compact Disc Player (model CDP-CE535) connected to the audiometer. Two Radio Ear B-71 bone vibrators (serial numbers 00864 and 00862) attached with elastic and Velcro strips were used to examine soundfield to bone and bone-to-bone loudness comparisons (Appendix D). The bone vibrators were located on either the condyle or mastoid placements unilaterally or bilaterally. The force of the bone vibrator against the head was measured by a Mark 10 series force gauge using the procedure described in Toll, Emanuel and Letowski (2011). The air conduction stimuli were presented through a loudspeaker positioned 3.5 feet in front of the subject at 0° azimuth. The subject was seated in a sound treated test room and the tester was seated in a separate room with sound proof glass separating the two rooms. The test room met maximum permissible ambient noise level standards (Frank, 2000). The tester and participant could see each other at all times during the testing. The study was conducted in the Towson University Institute for Well Being, Hearing and Balance Center.

Stimuli

The stimuli used in the study were 1 second long, one-third-octave bands of noise with a rise and fall time of 25 ms and plateau duration of 950 ms; these stimuli were digitally generated. These stimuli were developed by Pollard et al. (2013) and made available for this study. The original stimuli were modified in intensity as needed for this study using computer software (Audacity) and transferred to a CD. Stimuli were delivered to the participants using the CD player connected to the audiometer, allowing intensity changes separately in each channel. For bone-to–bone comparisons (see description under procedures), the noise stimulus in Channel 1, previously described, was one-third octave band of noise centered at 1000 Hz and presented at either 20 dB or 40 dB HL. Noise stimuli in Channel 2 were one-third octave noise centered at 250, 500, 1000, 2000, 3000, 4000, and 6000 Hz frequency (Note 1: high frequency limit for the Astera audiometer coupled to a B-71 bone vibrator is 6000 Hz). In Channel 1 and 2, stimuli were being played out of two bone vibrators in the bilateral bone to bone conditions. For bone to soundfield comparisons, the signal in channel 1 and channel 2 were the same and they were noises with a center frequency corresponding to one of the frequencies listed above. Channel 1 emitted a 40 dB HL reference noise band via the soundfield and the test stimuli were presented through channel 2 with the bone vibrator placed on the right mastoid. 20 dB HL was not tested in the bone to soundfield comparisons. For soundfield-to-soundfield, channel 1 emitted a 40 dB HL tone at various reference frequencies, while channel 2 emitted the test stimuli at various intensities.

Procedure

Three types of comparisons were made as part of the experiment. First, a soundfield-to-soundfield comparison was made. This was included as part of the training procedure and as a way to examine individual participant responses compared with normative ISO 226. 2003 equal loudness curves (ISO, 2003). This task was used to increase the validity of the other comparisons in this study. Second, a soundfield-to-bone conduction comparison was made. This task was done to provide additional data as a follow up to data collected by Pollard et al. (2013). Third, a bone-to-bone comparison using unilateral and bilateral stimulation was used to generate data not previously examined. The procedures for each of these three portions are explained below. All equipment and transducers were calibrated prior to and mid-way through experimental testing. The loudspeakers were calibrated by using a sound level meter at the distance of the seated participant at the height of the ears with the listener absent. The bone vibrators were calibrated using a B&K 4930 artificial mastoid.

Soundfield-to-Soundfield

To minimize participants' difficulty in comparing loudness of signals having different pitch, test instruction and the soundfield-to-soundfield training experiment were conducted for each participant before the main bone conduction collection data was started. Training included adjusting the loudness level for comparison of soundfield-to-soundfield stimuli. Instructions to participants are included as Appendix B. Test frequencies included in testing were 250, 500, 750, 1000, 2000, 3000, 4000, 6000, and 8000 Hz. Channel 1 presented a reference tone of 1000 Hz at 40 dB SPL and Channel 2 presented the test stimuli at the various frequencies. Stimuli were alternated between channels but both were directed through the same loudspeaker. The loudspeaker was located at a 0° angle from the participant. The participant signaled to the tester to increase or decrease the intensity of the Channel 2 stimuli until all of the tones appeared to be equally loud. The signal was increased or decreased in 2 dB steps for three trials. This procedure was repeated for each test frequency through Channel 2.

Soundfield-to-Bone

This task included comparison of loudness between air conduction stimuli via a loudspeaker and bone conduction stimuli via a bone vibrator. Channel 1 stimuli were presented through the loudspeaker and Channel 2 stimuli were presented through the bone vibrator. The stimuli were presented in both channels with noises centered at 250, 500, 1000, 2000, 3000, 4000, or 6000 Hz. Stimuli were alternating continuously between channels 1 and 2 with no gaps (Pollard et al., 2013). Stimulus intensity was increased or decreased by 1 dB steps with the examiner adjusting the attenuation of channel 2 of the audiometer per the patient's instruction. At the beginning of each trial, the channels were set to different intensity levels so as not to allow the participant to predict the amount of steps needed to equal the loudness from channel 2 to channel 1. The participant's tasks were to compare loudness of the bone conduction test stimulus to the air conduction (reference) stimulus and adjust the level of the former stimulus to be equally loud to the reference stimulus. The participant would then signal to the tester when they wanted the intensity increased or decreased and the tester made the adjustment on the attenuation dial on Channel 2 of the audiometer. The task was repeated for each frequency of the test stimulus. The intensity dial on the audiometer was increased or decreased in 2 dB steps. The location of the bone vibrator was on the right mastoid and was tested only in the unilateral condition. The orders of the test frequencies and intensities of the reference stimulus were randomized using an algorithm available at the website Random.org. Stimuli from channel 1 were the control stimuli. The participants were seated in a sound treated booth with the audiometer located on the other tester side of the booth. The participant was instructed to adjust the intensity of the bone conduction stimulus using a method of adjustment. The subject indicated to the tester to increase or decrease the intensity of the bone conduction stimulus so that it perceptually equal in loudness compared to the reference stimulus. In total, three ascending trials were included and the adjusted values were averaged.

Bone-to-Bone

The procedure for obtaining bone-to-bone equal loudness contours was the same as the procedure for soundfield-to-bone. However, the reference stimulus was presented at 20 and 40 dB HL via bone conduction and stayed at 1000 Hz. The stimulus from channel 1 (the reference frequency) and the test stimuli were presented alternatively through the same bone vibrator. The reference frequency was presented at 20 and 40 dB HL to obtain bone-to-bone equal loudness contours. The participant again used a method of adjustment, as mentioned above in the soundfield-to-bone section, to adjust the intensity dial on Channel 2 of the audiometer until the test frequency was perceptually equal in loudness compared to the reference stimulus.

Equipment Calibration and Data Conversion

Each figure in the results section and all data used for descriptive and inferential analysis were based upon raw data that had been adjusted for each frequency and measured output level differences between devices, as described below. Electroacoustic calibration of the 2-channel Astera audiometer was conducted a year prior to and midway through testing by a professional calibration company. The equipment was found to be in good working order, it met ANSI S3.6-2010 standards on all testing occasions, and minimal adjustments were needed at the mid-way calibration point. These minor adjustments were taken into account in data processing. Immediately prior to the study and at the mid-way point, the output was measured by the researchers of the study.

The value of the reference signal was always set to 20 dB HL or 40 dB HL, based on the audiometer dial reading, except in the soundfield condition, which only had a reference signal of 40 dB HL. All other raw data were audiometer dial readings that, in isolation, could not be compared.

In addition calibration issues had to be taken into account for bone conduction data because of equipment limitations. The two Radio Ear B-71 bone vibrators output levels were measured with a B&K artificial mastoid attached to a frequency spectrum analyzer, which reported the output with the label of "dB SPL." A conversion sheet was created which indicated the correspondence between the audiometer dial reading and the level from the analyzer. Only one bone vibrator output jack was available on the audiometer; therefore, one bone vibrator (00864) was connected to the bone vibrator output jack (channel 1, reference signal) and the other bone vibrator (00862) was connected to the earphone output jack from the audiometer (channel 2, comparison signal). For all frequencies, the reference signal presented via the audiometer was set to channel 1 to elicit a 20 dB HL or 40 dB HL output through the bone vibrator in the bone output (00864). The level of channel 2 was adjusted until the bone vibrator produced an almost identical output, with at most a 1.2 dB difference between the two channel outputs.

The values recorded for the conversion sheet are provided in Appendix C. These values provide a comparison between the output levels for each channel. For example, note, in the first table of Appendix C, the values associated with 1000 Hz. With the audiometer dial set to 20 dB HL, the analyzer reported the output level of the bone vibrator to correspond to 46.3 dB SPL. Channel 2 was adjusted until the bone vibrator connected to the earphone jack produced an almost identical level (46 dB SPL). Channel 2 had to be set to a much higher number, 71, for the outputs to be equal. The difference between the output levels for the two bone vibrators was used to correct for the difference between the outputs of the two bone vibrators in the different jacks, so the raw data could be adjusted such that all data would be reported using the same relative scale. In this case, 51 dB (71-20 from the table) had to be subtracted from the raw data (audiometer dial reading of channel 2) in order to compare the reference and comparison levels using the same scale.

Chapter 4

Results

Recall, the three researchers were responsible for data collection for ten participants and the data were combined for analysis. Each researcher was responsible for conversion of data to identical units and submission of an Excel data file. These files were then merged to include the data for all 30 participants. Some analyses were conducted and some tables and figures were created as a group. When one of the three took a primary role, it was indicated in the text. Sections of texts that are identical across the three thesis projects are cited as well. Line graphs, t-tests, and analysis of variance (ANOVA) were based upon data that had been adjusted to account for calibration factors, described below. All statistical analysis was conducted using Statistical Package for the Social Sciences (SPSS) software version 21.

Data analysis was divided into three distinct parts. Part one was conducted by Arvindekar (2015), part two was conducted by Andreaggi (2015) and part three was conducted by this author and is described in this thesis. Specifically, this thesis focused on examining similarities and differences between mastoid and condyle placements and between two different intensity levels referents (20 and 40 dB HL). In addition, comparisons between soundfield and bone conduction loudness contours were examined. The results section is comprised of all the testers' data figures, and statistical analysis. Statistical analysis includes using a repeated measures analysis of variance (ANOVA) to compare laterality, placements, frequency, and intensity differences in the bone conduction data. To compare ISO data and published data to the soundfield, soundfield-to-bone and bone conduction data from the current study paired sample t-tests were used.

To compare gender and tester differences and possible interaction effects, a two-way Factorial ANOVA was used. Statistical Analysis for each comparison is described in detail in the Data Analysis and Discussion Section.

Equal Loudness Contours

Figure 1 illustrates a comparison between our study's soundfield data, ISO (2003) data, and the average of all the bone conduction curves when the intensity level of the reference was set to 40 dB HL. The soundfield equal loudness contours from the current study were lower than the established ISO 2003 values for soundfield at 40 dB at all tested frequencies except 6000 Hz. The loudness values were similar except at 250 Hz, where they were approximately 10 dB different. The average bone conduction curve closely approximates soundfield data from the current study, except at 6000 Hz, where the bone conduction value was approximately 10 dB lower than the soundfield value. Figure 2 illustrates a comparison between our study's soundfield data, ISO (2003) data, and the published data from Pollack (1952) when the intensity level of the reference was set to 40 dB HL. The soundfield equal loudness contours from the current study were almost identical to the ISO 2003 values except at 250, 6000 and 8000 Hz, where they were approximately 10-12 dB lower. The Pollack (1952) curve closely approximates soundfield data from the current study, except at 250, where the soundfield value is approximately 9 dB lower. Figure 3 illustrates a comparison between our study's soundfield data, ISO (2003) data, and Pollack (1952) data at 40 dB HL. In addition, the line graph includes this study's soundfield-to-bone data and published data from Patrick et al. (2012), Stenfelt and Hakansson (2002), and Pollard et al. (2013). The loudness values were similar except at 250 Hz, where they were approximately 10 dB different.

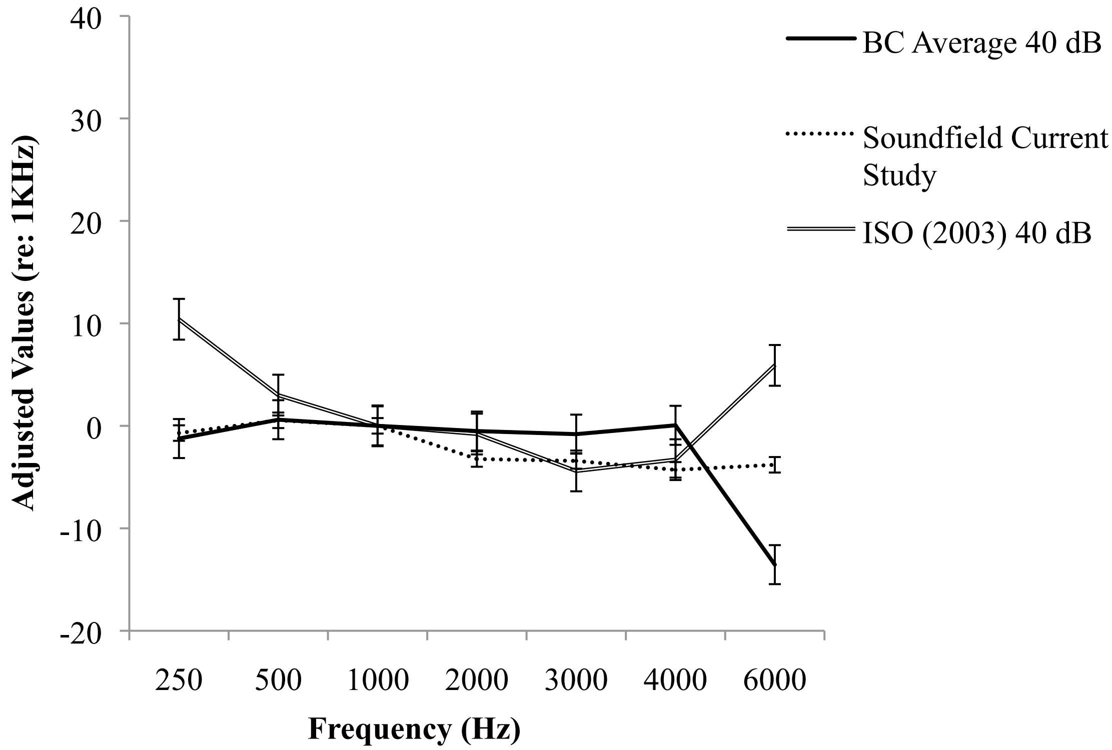

Figure 1. Adjusted mean values as a function of frequency for the soundfield current study data, the ISO 2003 curve, and the average bone conduction curve determined with a 1000 Hz reference set to 40 dB HL. For all of the ISO 2003 published values 3150 Hz value was used for 3000 Hz and 6300 Hz was used for 6000 Hz

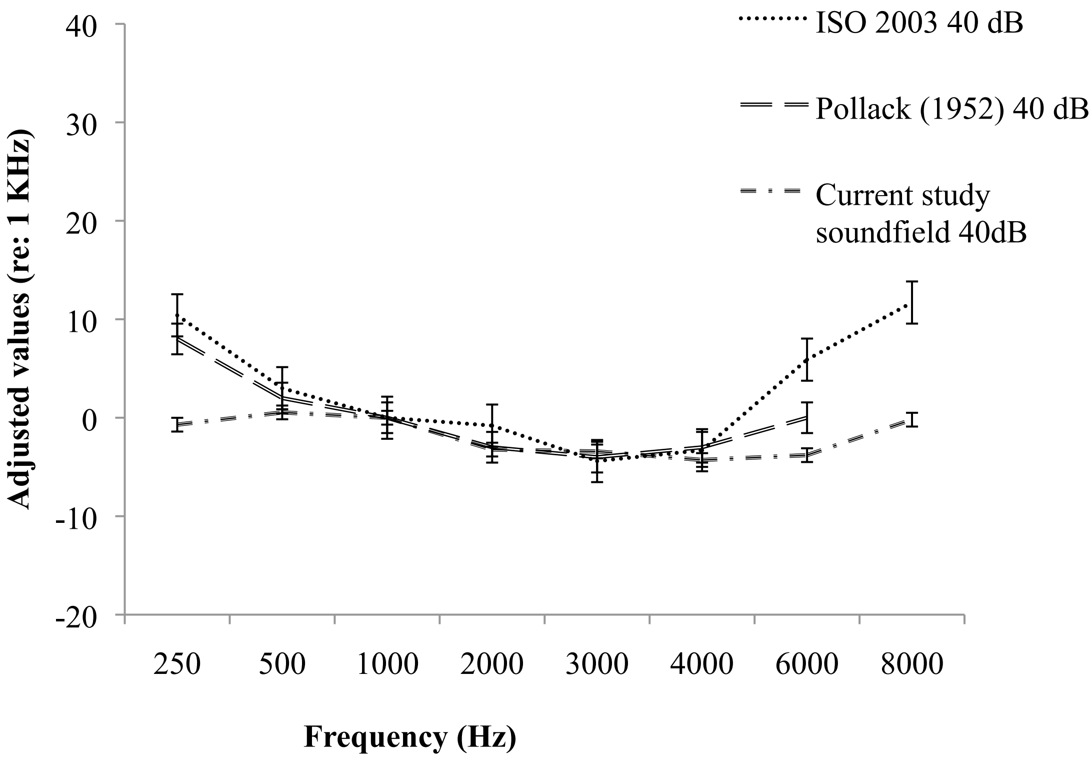

Figure 2. Adjusted mean values as a function of frequency for the soundfield current study data determined with a 1000 Hz reference set to 40 dB HL, the ISO 2003 curve, and the published data from Pollack (1952) at 40 dB HL.

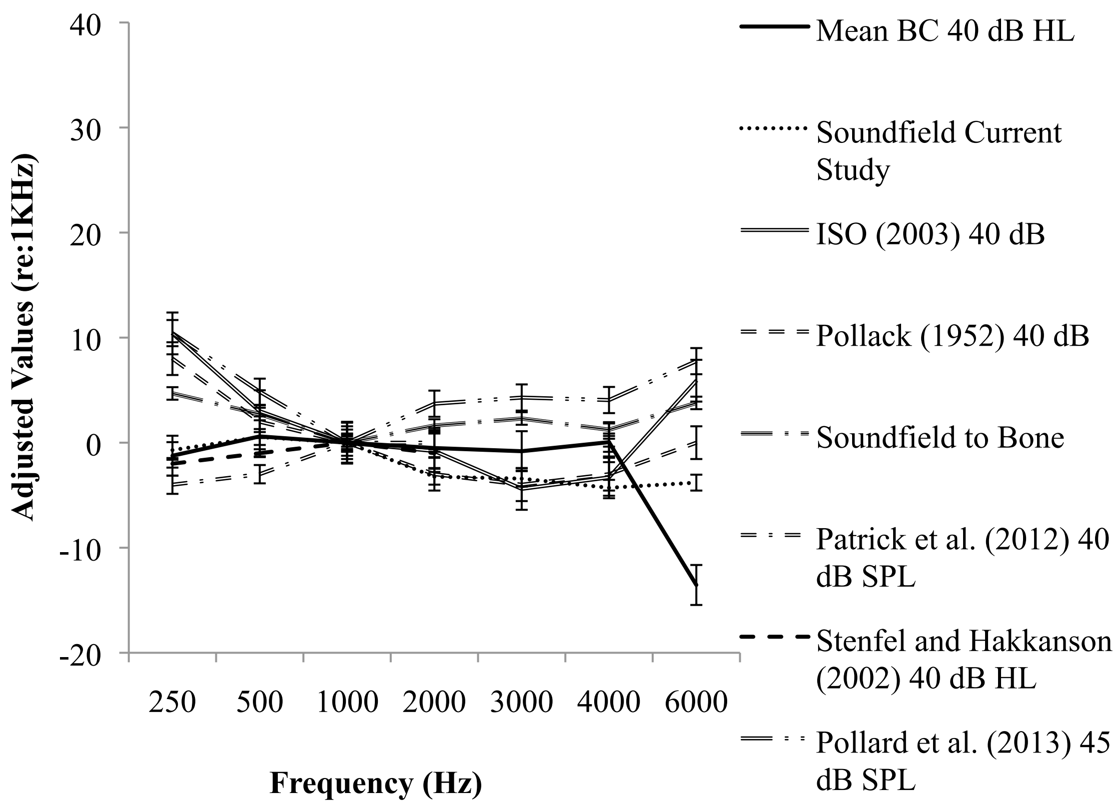

Figure 3. Adjusted mean values as a function of frequency for the current study's soundfield data determined with a 1000 Hz reference set to 40 dB HL, ISO 2003 data, and Pollack (1952) data at 40 dB HL. In addition, the line graph includes this study's soundfield-to-bone data and published data from Patrick et al. (2012), Stenfelt and Hakansson (2002), and Pollard et al. (2013). For the Pollard et al. (2013) values, 3150 Hz was used in the graph to replace 3000 Hz, and 6300 Hz was used to replace 6000 Hz.

The average bone conduction curve closely approximates soundfield data from the current study, except at 6000 Hz, where the bone conduction value was approximately 10 dB lower than the soundfield value. The Pollack (1952) curve closely approximates soundfield data from the current study, except at 250, where the soundfield value was approximately 9 dB lower. The soundfield equal loudness contours from the current study did not closely approximate the Pollard et al. (2013) curve across all of the test frequencies. The soundfield curve from the current study was approximately 4 -10 dB lower than the Pollard et al. (2013) curve. The soundfield equal loudness contours from the current study approximated the Patrick et al. (2012) values except at 250 and 500 Hz, where they were approximately 3-4 dB different. Compared to the Stenfelt and Hakansson (2002) values, the soundfield equal loudness values from the current study were almost identical, with a difference between the two curves not exceeding 3 dB. The soundfield equal loudness contours closely approximates soundfield data from the current study, with slight difference of approximately 4 dB at 2000, 3000, and 4000 Hz.

Figure 4 illustrates the bone conduction values for unilateral mastoid, bilateral mastoid, unilateral condyle and bilateral condyle at 20 dB HL compared to the published ISO values for 20 dB and the soundfield loudness contour values from the current study. All of the bone conduction equal loudness contours were similar to each other as well as to the published ISO values for 20 dB. The bone conduction equal loudness values were lower than the established ISO 2003 values for soundfield at 20 dB at all tested frequencies, except at 2000 and 4000 Hz. Differences were quite small, except at 250 and 6000 Hz, where they were approximately 3-8 dB different.

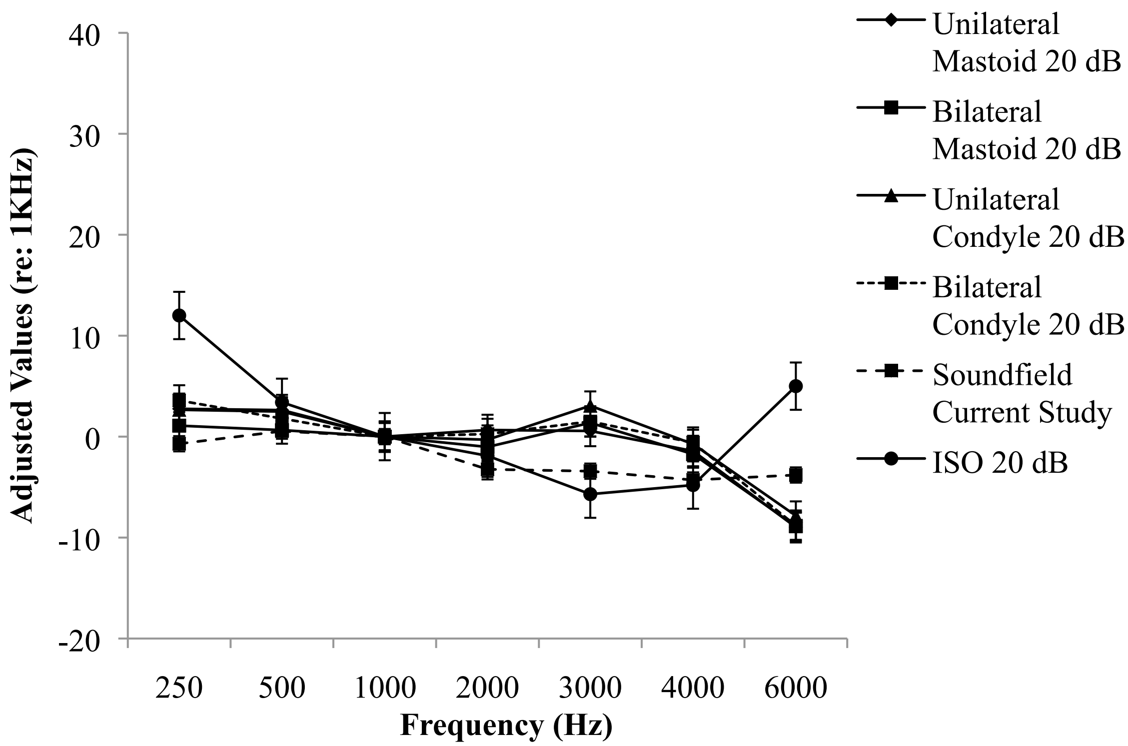

Figure 4. Adjusted mean values as a function of frequency for the unilateral mastoid, bilateral mastoid, unilateral condyle, and bilateral condyle determined with a 1000 Hz reference set to 20 dB HL.

The soundfield equal loudness curve from the current study, approximates bone conduction data from the current study, except at 3000 and 6000 Hz, where the soundfield value was approximately 3 dB lower than the bone conduction value.

Figure 5 illustrates the bone conduction values for unilateral mastoid, bilateral mastoid, unilateral condyle and bilateral condyle at 40 dB HL compared to the published ISO values for 40 dB and the soundfield loudness contour values from the current study. All of the bone conduction equal loudness contours were similar to each other as well as to the published ISO values for 40 dB. The bone conduction equal loudness values were lower than the established ISO 2003 values for soundfield at 40 dB at all tested frequencies, except at 2000 and 4000 Hz. Differences were quite small, except at 250 and 6000 Hz, where they were approximately 8-10 dB different. The soundfield equal loudness curve from the current study, approximates bone conduction data from the current study, except at 3000, 4000 and 6000 Hz, where the soundfield value was approximately 3 dB lower than the bone conduction value.

Soundfield to bone conduction loudness level comparisons indicated loudness levels were similar across all test frequencies regardless of delivery modality (Figure 6). The figure below included published data from Patrick et al. (2012), Pollard et al. (2013) and Stenfelt and Hakansson (2002) studies which examined equal loudness contour comparisons between soundfield and bone conduction stimuli. Patrick et al. (2012) conducted their study using a 40 dB SPL air conduction reference tone, Stenfelt and Hakansson (2002) used a 40 dB HL air conduction reference tone which is the same intensity used in this study, and Pollard et al. (2013) used a 45 dB SPL air conduction reference tone.

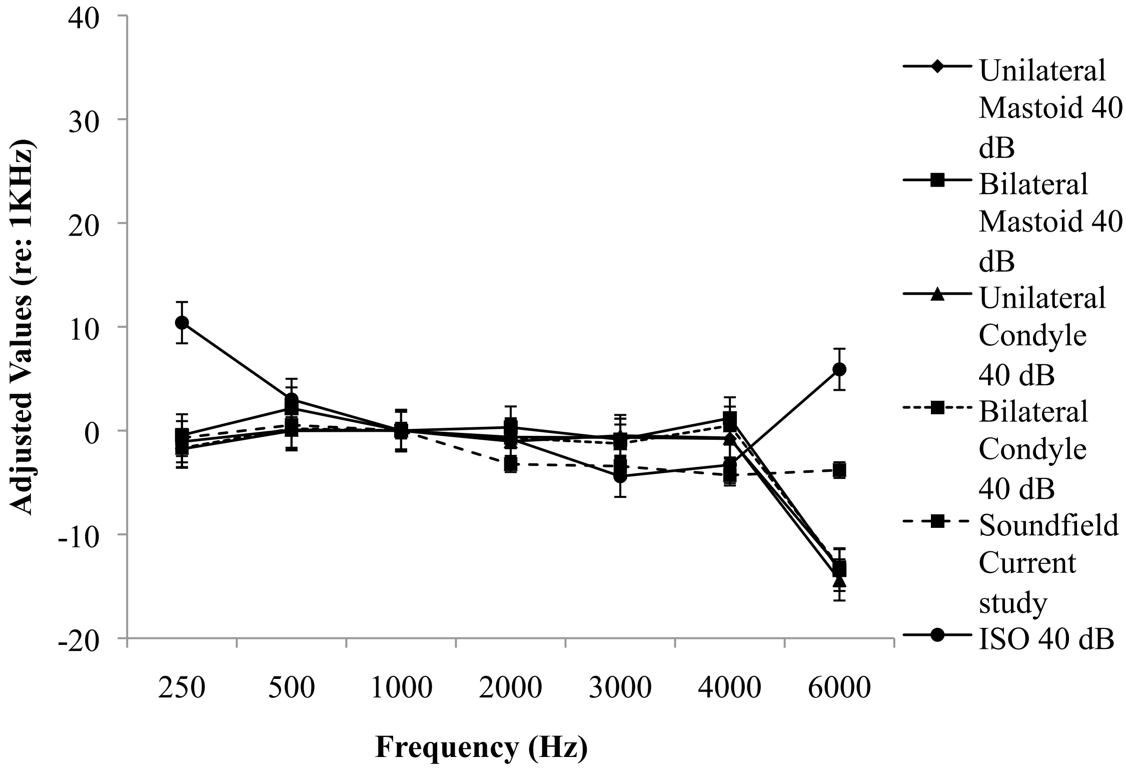

Figure 5. Adjusted mean values as a function for the unilateral mastoid, bilateral mastoid, unilateral condyle, and bilateral condyle determined with a 1000 Hz reference set to 40 dB HL.

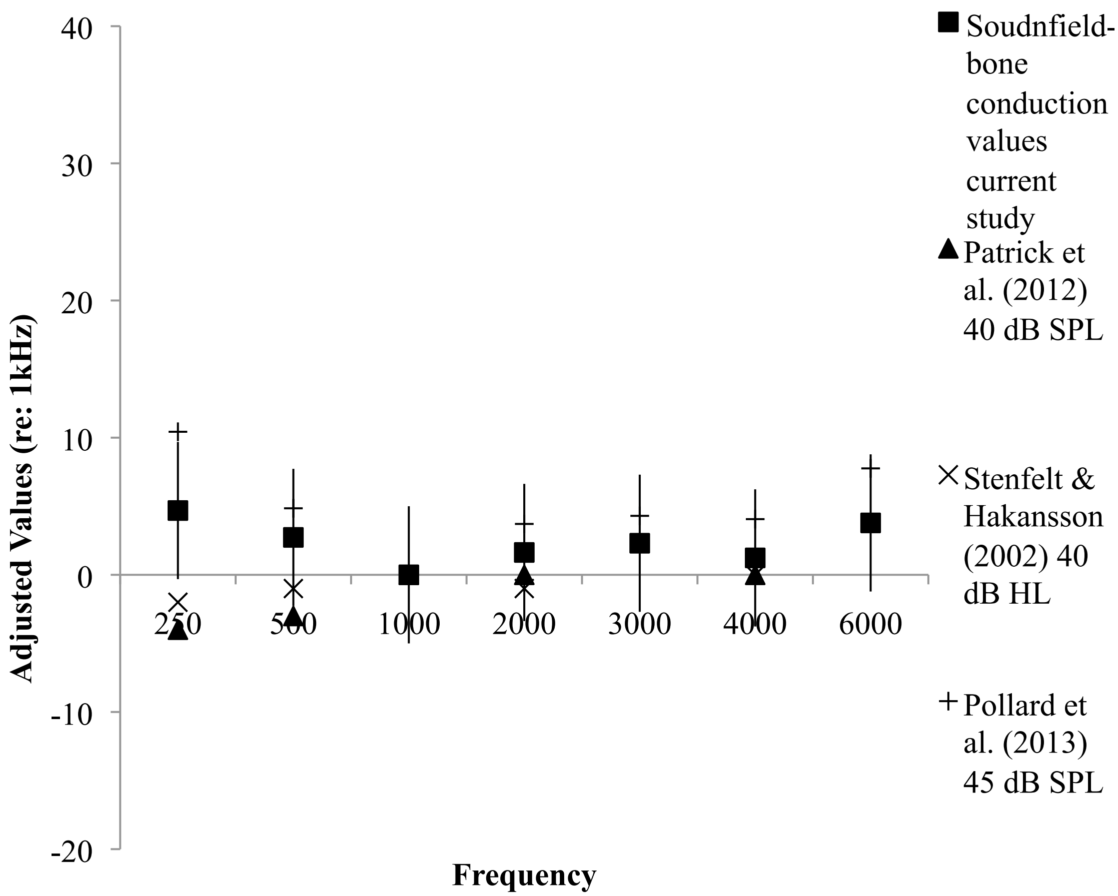

Figure 6. Adjusted mean values as a function of frequency for mean participant unilateral mastoid bone conduction values compared to a reference soundfield value presented at 40 dB HL and published data from Patrick et al. (2012), Pollard et al. (2013) and Stenfelt & Hakansson (2002). For the Pollard et al. (2013) values, 3150 Hz was used in the graph to replace 3000 Hz, and 6300 Ha was used to replace 6000 Hz.

As is indicated in the figure, the general trend for the Stenfelt and Hakansson (2002) and Patrick et al. (2012) studies is that less intensity is needed for bone conduction loudness levels to have equal loudness compared to the soundfield reference tone at 0 dB. The soundfield-to-bone values from the current study were higher than the soundfield reference tone equalized at 0 dB at all tested frequencies. Differences were quite small, with differences between the value from the current study and the reference tone equalized at 0 dB not exceeding 5 dB. The Stenfelt and Hakansson (2002) curve closely approximates the soundfield-to-bone data from the current study, except at 250, where the Stenfelt and Hakansson (2002) value is approximately 6 dB lower. The Patrick et al. (2012) values were almost identical to the soundfield-to-bone values, except at 250 and 500 Hz, where it was approximately 10 dB different. The Pollard et al. (2013) data did not closely approximate the values from the current study across all tested frequencies, where the Pollard et al. (2013) values were 2-6 dB higher.

Laterality

Figure 7 illustrates a comparison between the unilateral and bilateral condition at the condyle placement at a 1000 Hz reference tone at an intensity level of 40 dB HL. The contours show a pattern that indicates that laterality had similar contours in morphology and proportion. Examination of Figure 7 indicates that there are slight differences of 2-3 dB between laterality at each test frequency, especially in the higher frequencies (4000-6000) where the bilateral condition has slightly larger mean adjusted values compared to the unilateral condition. Figure 8 illustrates a comparison between the unilateral and bilateral condition at the mastoid placement at an intensity level of 40 dB HL.

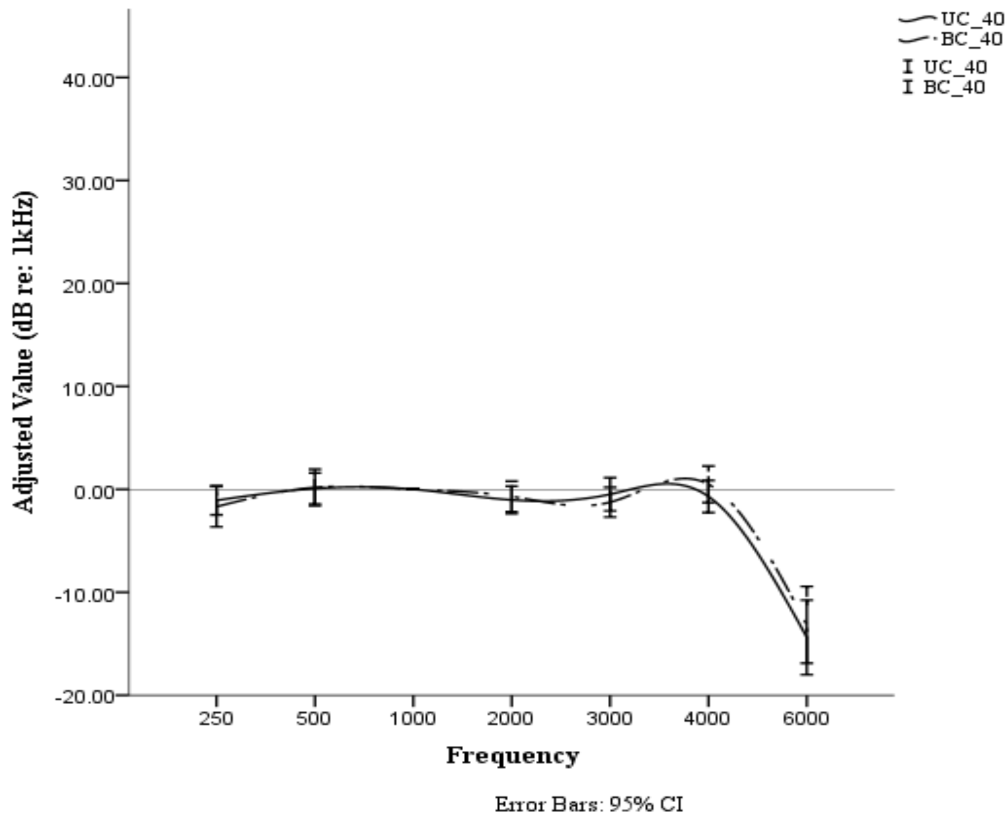

Figure 7. Adjusted mean values as a function of frequency in unilateral and bilateral condyle condition determined with a 1000 Hz reference set to 40 dB HL.

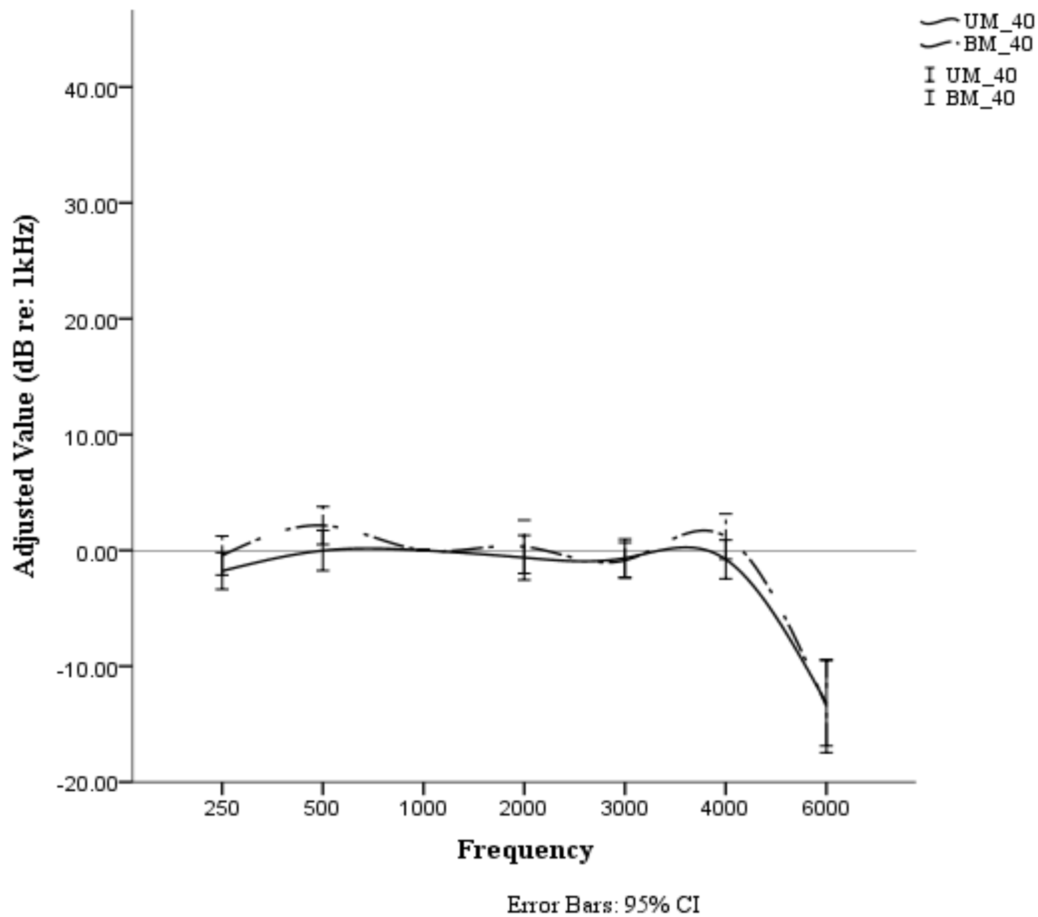

Figure 8. Adjusted mean values as a function of frequency in unilateral and bilateral mastoid condition determined with a 1000 Hz reference set to 40 dB HL.

The contours show a pattern that indicates that both conditions create similar contours in morphology and proportion. Examination of figure 8 indicated that there are slight differences of 2-3 dB between laterality at each test frequency, especially at the lower frequencies (250-500 Hz) and higher frequencies (4000-6000 Hz) where the bilateral condition has slightly larger mean adjusted values compared to the unilateral condition.

Figure 9 illustrates a comparison between the unilateral and bilateral condition at the condyle placement to a 1000 Hz reference tone at an intensity level of 20 dB HL. The contours show a pattern that indicates that laterality has similar contours in morphology and shape of the curve. Examination of Figure 9 indicates that there are slight differences of 2-3 dB in laterality at each test frequency, especially at 500 and 3000 Hz where the bilateral condition has slightly smaller mean adjusted values compared to the unilateral condition.

Figure 10 illustrates a comparison between the unilateral and bilateral condition at the mastoid placement to a 1000 Hz reference tone at an intensity level of 20 dB HL. The contours show a pattern that indicates that both conditions create similar contours in morphology and shape of the curve. Examination of figure 10 indicated that there are slight differences of 2-3 dB between laterality at each test frequency, especially at the lower frequencies (250-500 Hz) where the bilateral condition has slightly smaller mean adjusted values compared to the unilateral condition.

Placement

Figure 11 illustrates a comparison between the mastoid and condyle placement in the unilateral condition at an intensity level of 40 dB HL. The contours show a pattern that indicates that both placements create similar contours in morphology and proportion.

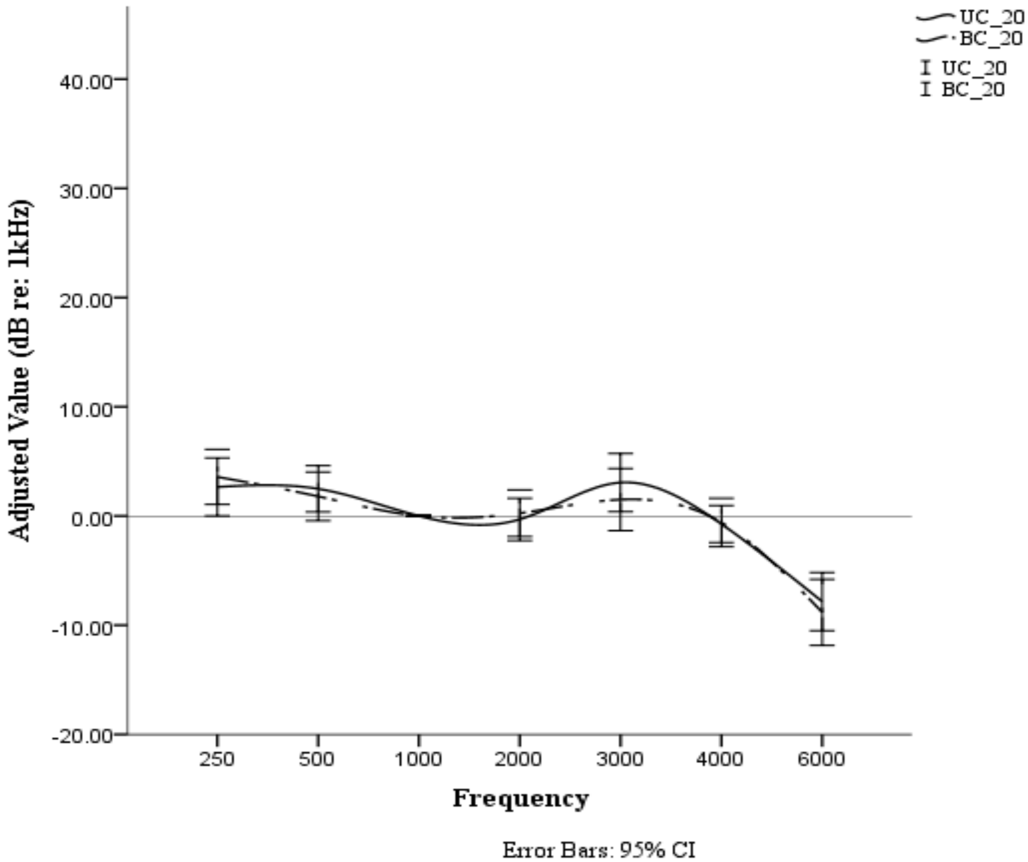

Figure 9. Adjusted mean values as a function of frequency in unilateral and bilateral condyle condition determined with a 1000 Hz reference set to 20 dB HL.

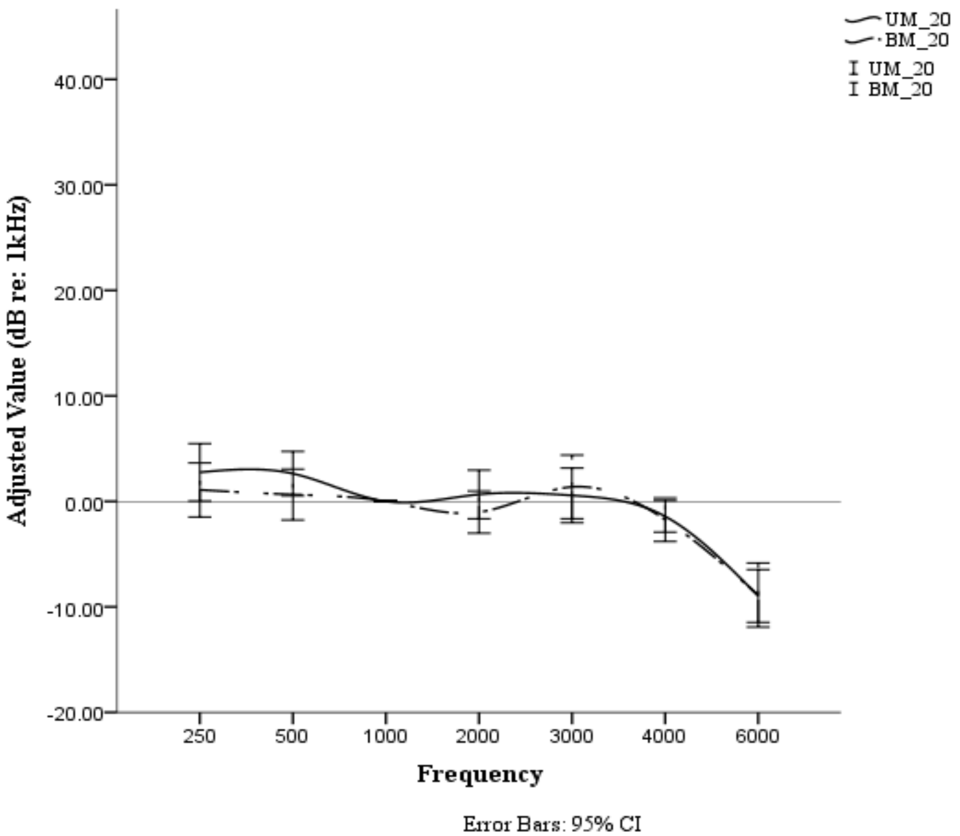

Figure 10. Adjusted mean values as a function of frequency in unilateral and bilateral mastoid condition determined with a 1000 Hz reference set to 20 dB HL.

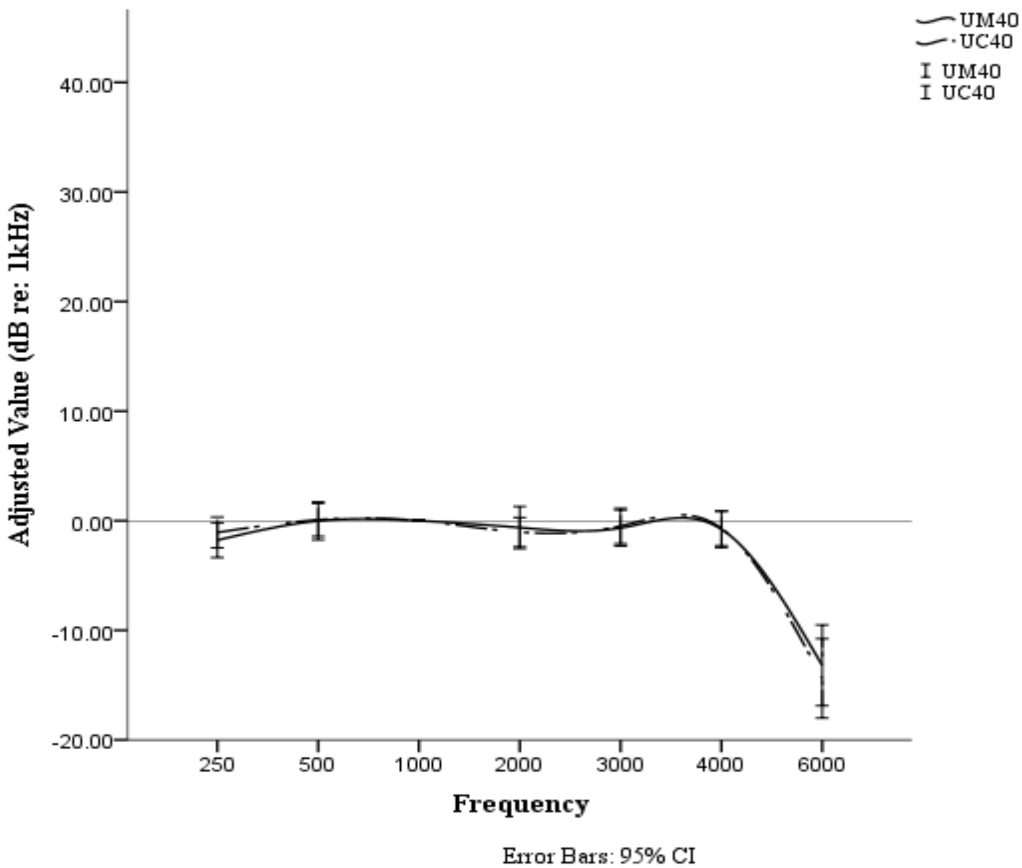

Figure 11. Adjusted mean values as a function of frequency in the unilateral condition at the mastoid and condyle placement determined with a 1000 Hz reference set to 40 dB HL.

Examination of figure 11 indicates that there are slight differences of 1 dB or less between the two placements at each test frequency, with differences not exceeding 2 dB.

Figure 12 illustrates a comparison between the mastoid and condyle placement in the bilateral condition to a 1000 Hz reference tone at an intensity level of 40 dB HL. The contours show a pattern that indicates that both placements create similar contours in morphology and proportion. Examination of figure 12 indicated that there are slight differences of 2-3 dB between the two placements at each test frequency, especially at the lower frequencies (250-500 Hz) and higher frequencies (2000-4000) where the condyle placement has slightly smaller mean adjusted values compared to the mastoid placement.

Figure 13 illustrates a comparison between the mastoid and condyle placement in the bilateral condition to a 1000 Hz reference tone at an intensity level of 20 dB HL. The contours show a pattern that indicates that both conditions create similar contours in morphology and proportion. Examination of figure 13 indicated that there are slight differences of 2-4 dB between the two placements at each frequency, especially at the lower frequencies (250-500 Hz) and higher frequencies (2000, 4000, and 6000 Hz) where the condyle condition has slightly larger mean adjusted values compared to the mastoid placement.

Figure 14 illustrates a comparison between the mastoid and condyle placement in the unilateral condition t a 1000 Hz reference tone at an intensity level of 20 dB HL. The contours show a pattern that indicates that both conditions create similar contours in morphology and proportion. Examination of figure 14 indicated that there are slight differences of 2-3 dB between the two placements at each frequency, especially at 2000 Hz where the condyle placement had slightly smaller mean adjusted values and at 3000

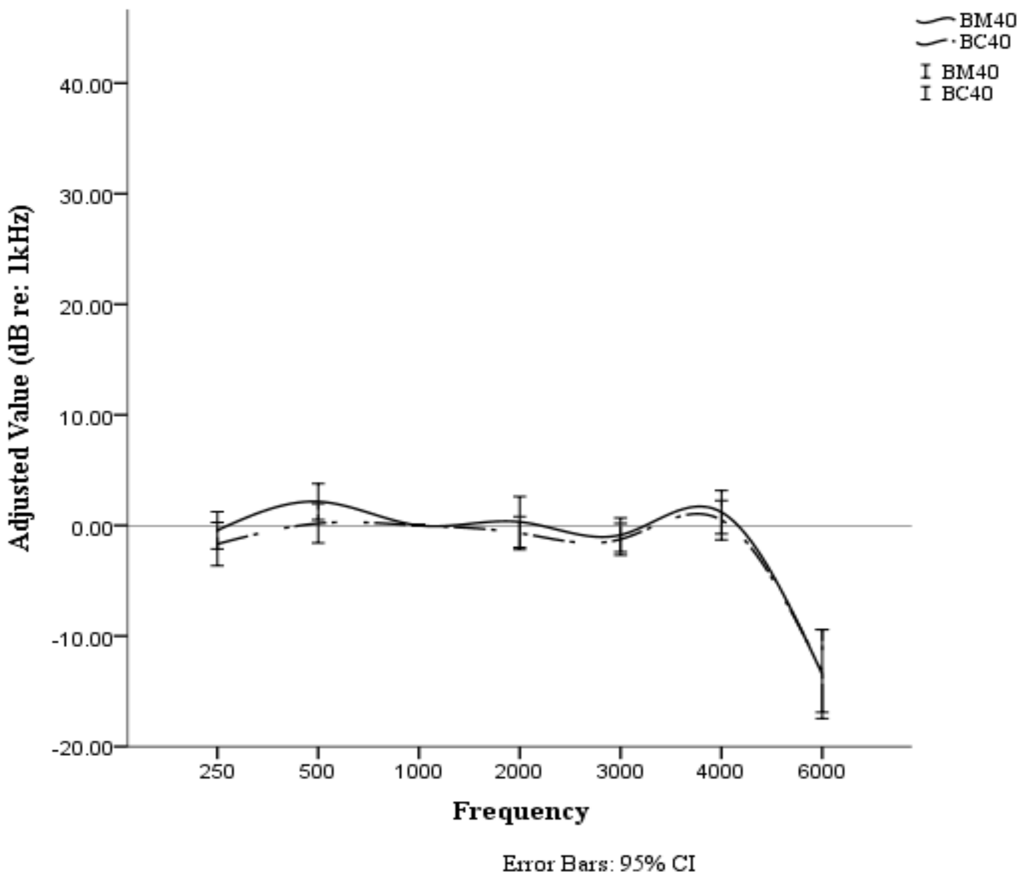

Figure 12. Adjusted mean values as a function of frequency in the bilateral condition at the mastoid and condyle placement determined with a 1000 Hz reference set to 40 dB HL.

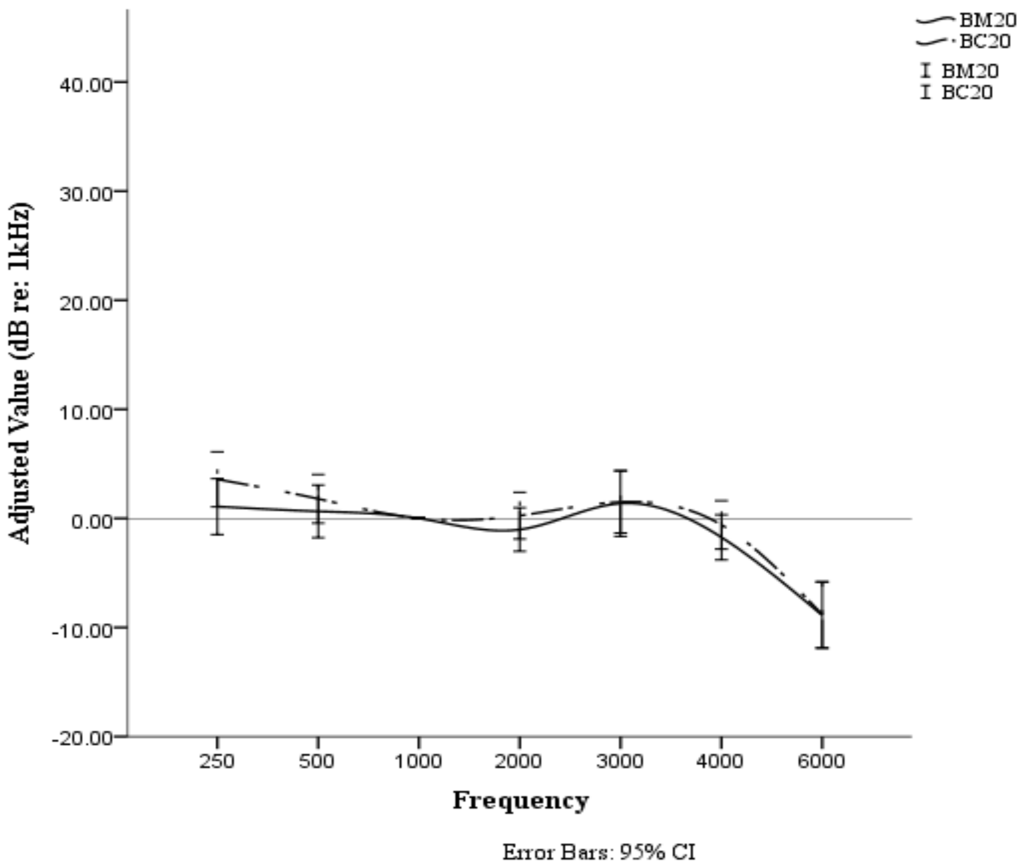

Figure 13. Adjusted mean values as a function of frequency in the bilateral condition at the mastoid and condyle placement determined with a 1000 Hz reference set to 20 dB HL.

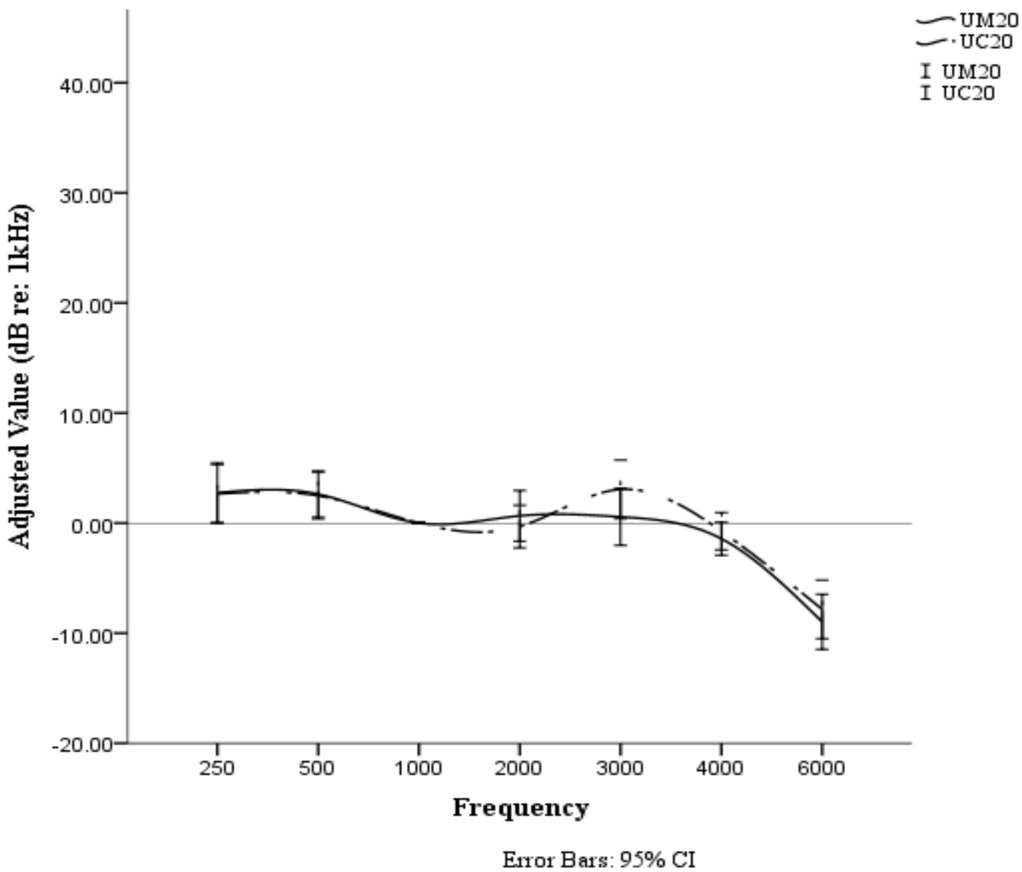

Figure 14. Adjusted mean values as a function of frequency in the unilateral condition at the mastoid and condyle placement determined with a 1000 Hz reference set to 20 dB HL.

4000 Hz where the condyle placement has slightly larger mean adjusted values compared to the mastoid placement.

Intensity

Figure 15 illustrates a comparison between the test intensities (20 and 40 dB HL) in the bilateral condition at the mastoid placement. The contours show a pattern that indicates that both intensities create similar contours in morphology and proportion. Examination of figure 15 indicates that there are slight differences between the two intensities at each test frequency, especially at 500, 2000, and 4000 Hz where the 40 dB HL contour has slightly larger mean adjusted values by approximately 2-3 dB compared to the 20 dB HL contour. The intensity of 20 dB HL had slightly higher values by approximately 2-3 dB at 250, 3000, and 600 Hz.

Figure 16 illustrates a comparison between the test intensities (20 and 40 dB HL) in the bilateral condition at the condyle placement. The contours show a pattern that indicates that both intensities create similar contours in morphology and proportion. Examination of figure 16 indicates that there are slight differences of approximately 3-5 dB between the two intensities at each test frequency, especially at the lower (250-500 Hz) and higher frequencies (2000-3000 Hz) where the 40 dB HL contour has slightly smaller mean adjusted values compared to the 20 dB HL contour.

Figure 17 illustrates a comparison between the test intensities (20 and 40 dB HL) in the unilateral condition at the mastoid placement. The contours show a pattern that indicates that both intensities create similar contours in morphology and proportion. Examination of figure 17 indicates that there are slight differences of 3-4 dB between the two intensities at each test frequency, especially at the lower 250-500 Hz) and higher

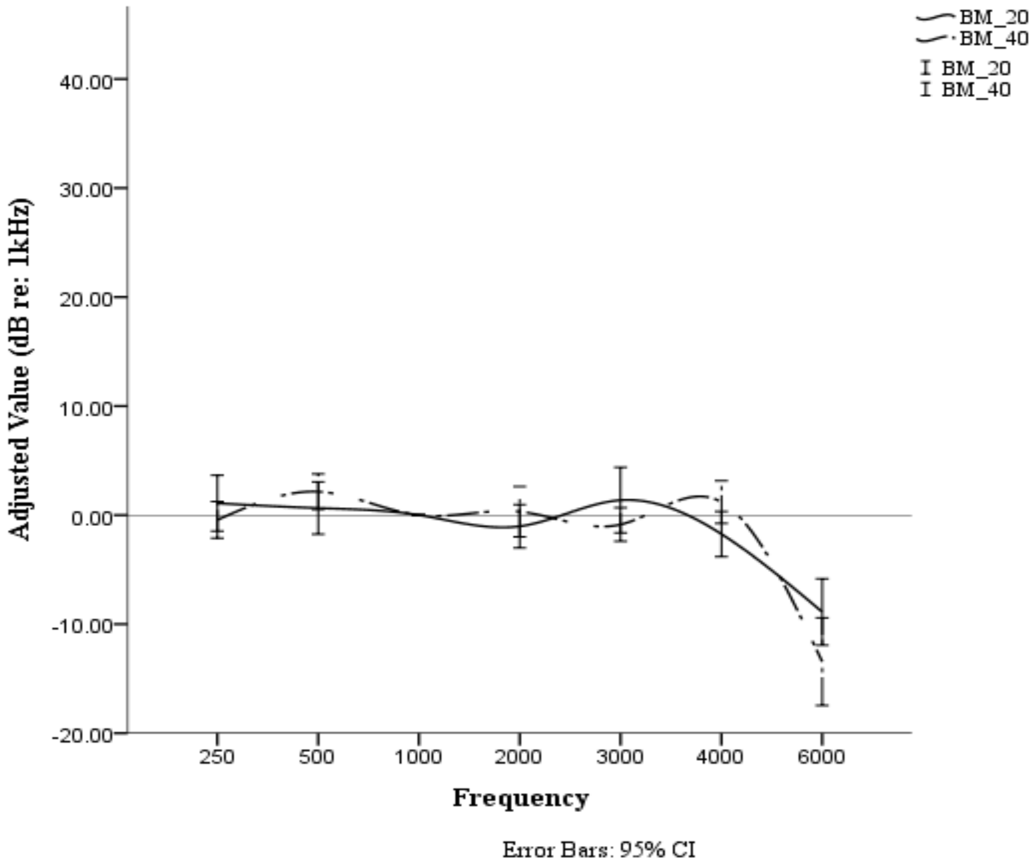

Figure 15. Adjusted mean values as a function of frequency in the bilateral mastoid condition determined with a 1000 Hz reference set to 20 and 40 dB HL.

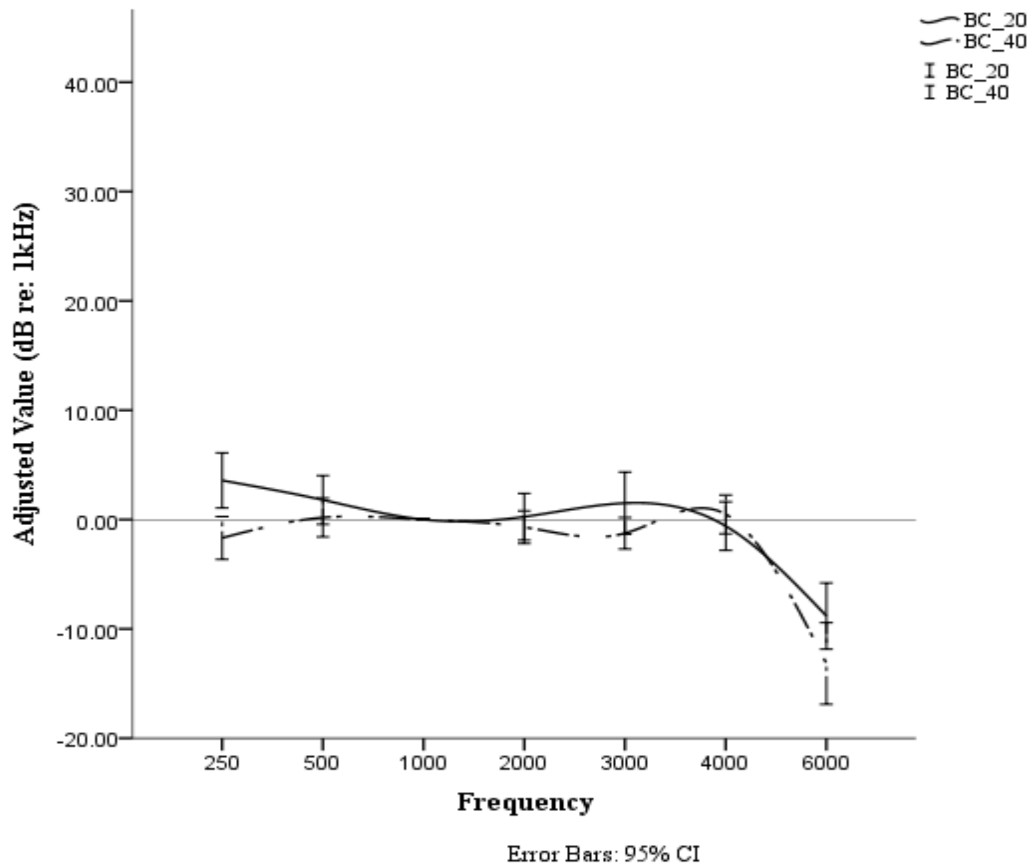

Figure 16. Adjusted mean values as a function of frequency in the bilateral condyle condition determined with a 1000 Hz reference set to 20 and 40 dB HL.

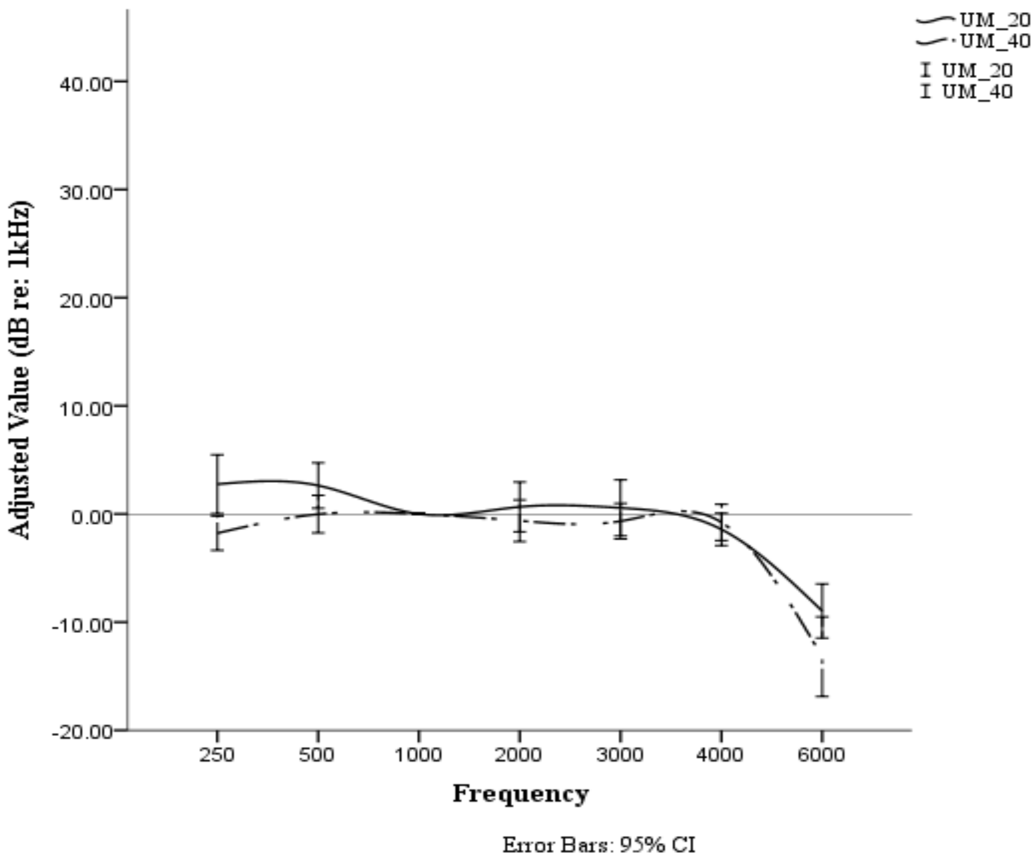

Figure 17. Adjusted mean values as a function of frequency in the unilateral mastoid condition determined with a 1000 Hz reference set to 20 and 40 dB HL.

frequencies (2000-3000, 6000 Hz) where the 40 dB HL contour has slightly smaller mean adjusted values compared to the 20 dB HL contour.

Figure 18 illustrates a comparison between the test intensities (20 and 40 dB HL) in the unilateral condition at the mastoid placement. The contours show a pattern that indicates that both intensities create similar contours in morphology and proportion. Examination of figure 18 indicates that there are slight differences of 3-5 dB between the two intensities at each test frequency, especially at the lower (250-500 Hz) and higher frequencies (2000-3000, 6000 Hz) where the 40 dB HL contour has slightly smaller mean adjusted values compared to the 20 dB HL contour.

Figure 19 represents the soundfield-to-soundfield comparisons separated by tester and frequency as well as published ISO 2003 equal loudness contour values for 40 dB HL. The Soundfield-to-soundfield loudness comparisons were used as training for the bone-to-bone and air-to-bone comparisons. Examination of the figure reveals similar morphology of the responses between all three tester's participants as well as ISO 2003 loudness contour values. All the testers closely matched the each other and the published ISO values for 40 dB SPL in the lower frequencies of 250, 500, and 1000 Hz and in the higher frequency of 8000 Hz. Tester three was the farthest from the published ISO values with a difference ranging from 3 to 15 dB in the mid frequencies of 2000 to 6000 Hz. Tester two was the closest to the published ISO values with a difference ranging from 2 to 5 dB in the mid frequencies of 2000 to 6000 Hz. Tester one had differences ranging from 3 to 10 dB in the mid frequencies of 2000 to 6000 Hz.

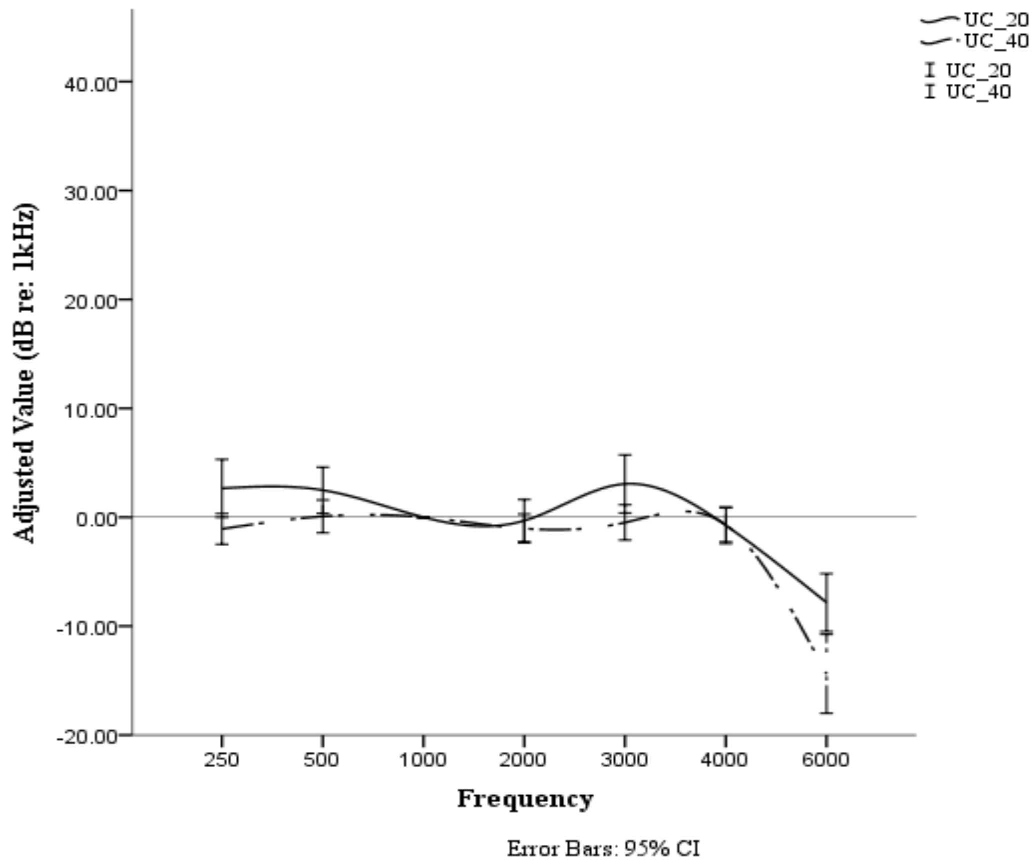

Figure 18. Adjusted mean values as a function of frequency in the unilateral condyle condition determined with a 1000 Hz reference set to 20 and 40 dB HL.

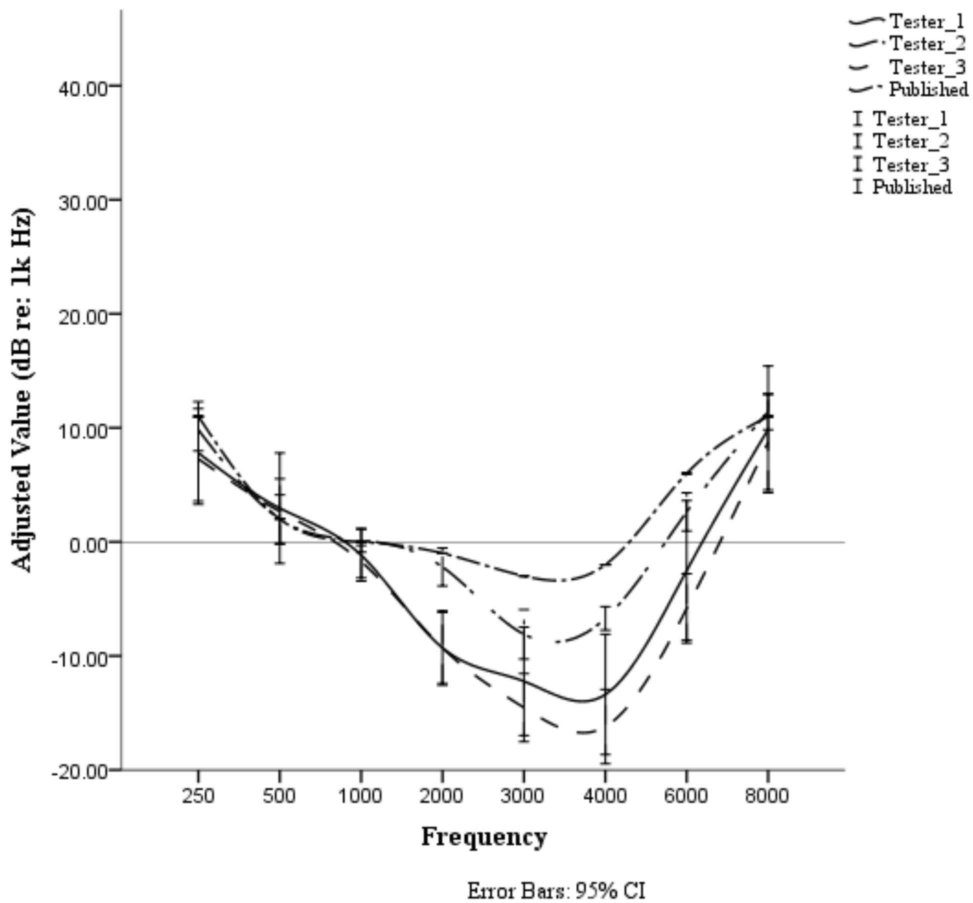

Figure 19. Adjusted mean values for each tester and the published ISO 2003 loudness values determined with a 1000 Hz reference set to 40 dB HL.

Figure 20 illustrates a comparison between male and female participants averaged across all bone conduction conditions determined with 1000 Hz reference set to 20 dB HL. Examination of the figure indicates that male participants had higher values by 5 dB in the lower frequencies of 250 and 500 Hz. No differences were observed in the higher frequencies (2000-3000 Hz).

Figure 21 illustrates a comparison between male and female participants averaged across all bone conduction conditions determined with 1000 Hz reference set to 40 dB HL. Examination of the figure indicates a difference of approximately 5 dB between male and female participants at 250 Hz. No differences were observed in the higher frequencies (2000-3000 Hz).

Figure 22 illustrates a comparison, separated by tester, between male participants averaged across all bone conduction conditions determined with 1000 Hz reference set to 40 dB HL. Examination of figure 25 indicates that tester two had higher values at 250 and 2000 Hz by approximately 3 dB when compared to testers one and three. Tester two had lower values at 500 Hz by approximately 2-3 dB and at 6000 Hz by approximately 20 dB when compared to tester two and three.

Figure 23 illustrates a comparison, separated by tester, between female participants averaged across all bone conduction conditions determined with 1000 Hz reference set to 40 dB HL. Examination of figure 23 indicates that tester one had lower values at 6000 Hz by approximately 20 dB when compared to testers two and three. Tester two had higher values at 500 Hz by approximately 3-5 dB when compared to testers one and three and was higher at 4000 Hz by 2-5 dB when compared to tester one

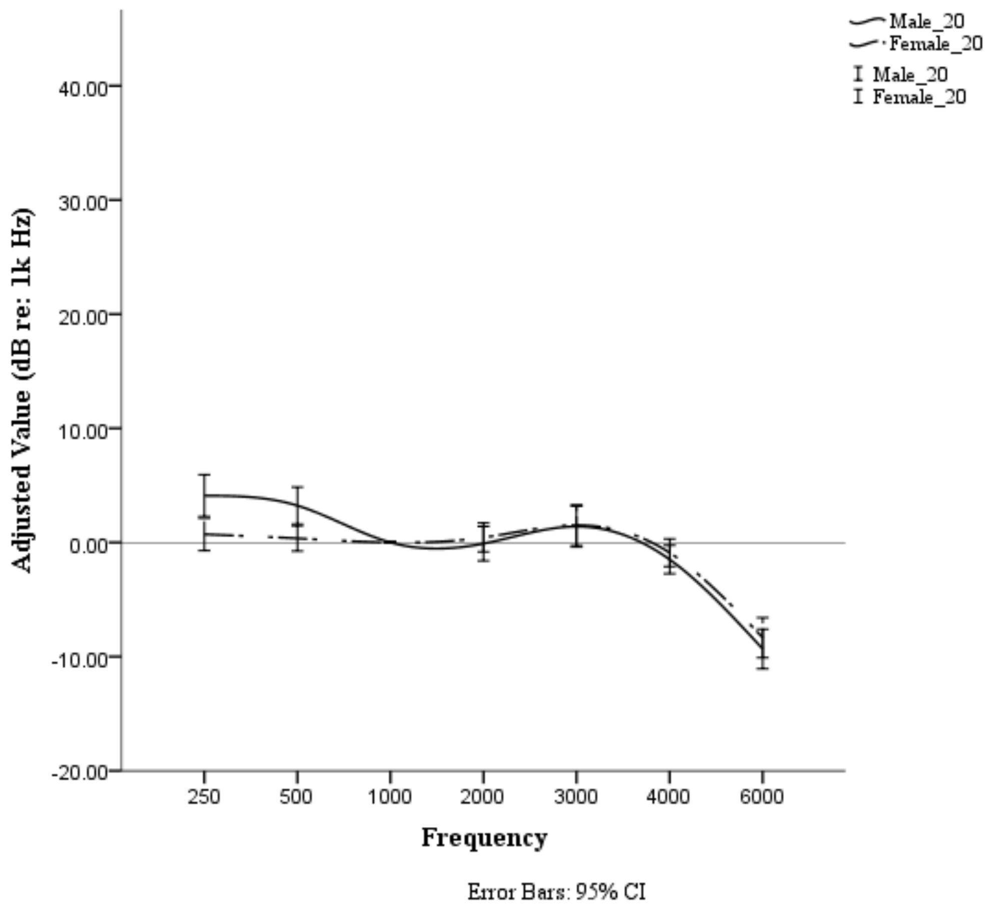

Figure 20. Adjusted mean values separated by gender for all bone conduction conditions with a 1000 Hz reference set to 20 dB HL.

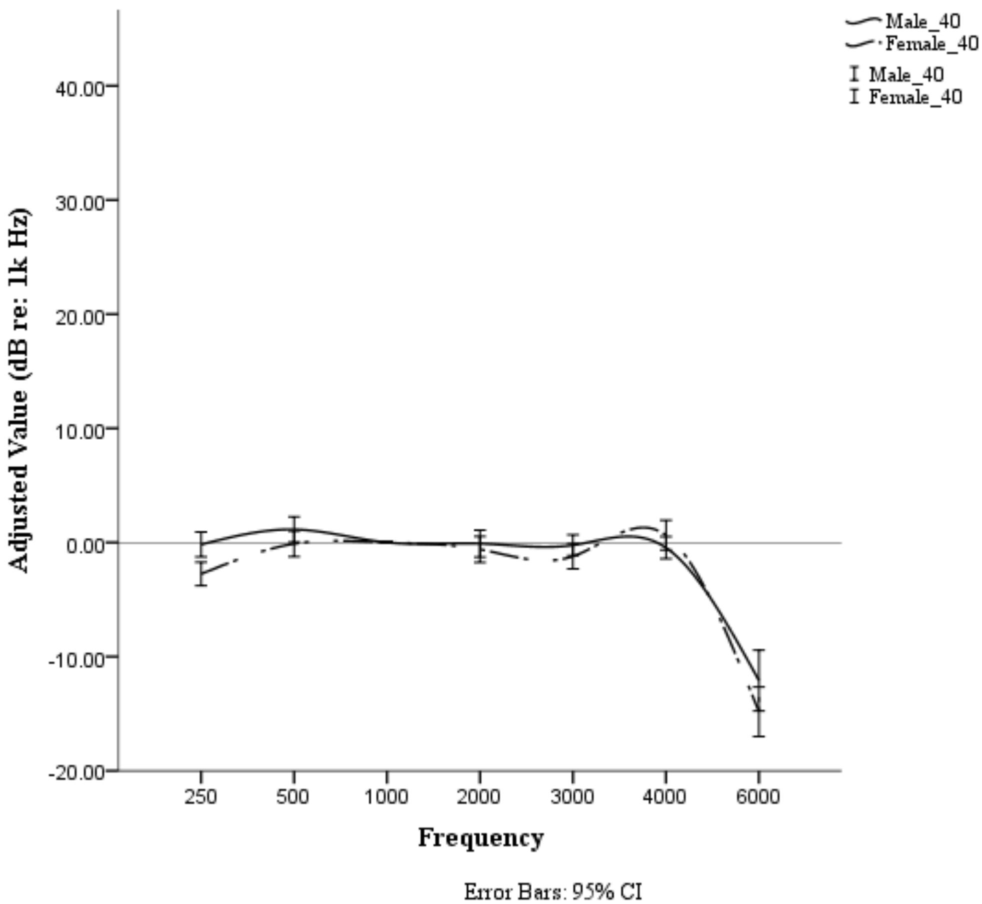

Figure 21. Adjusted mean values separated by gender for all bone conduction conditions with a 1000 Hz reference set to 20 dB HL.

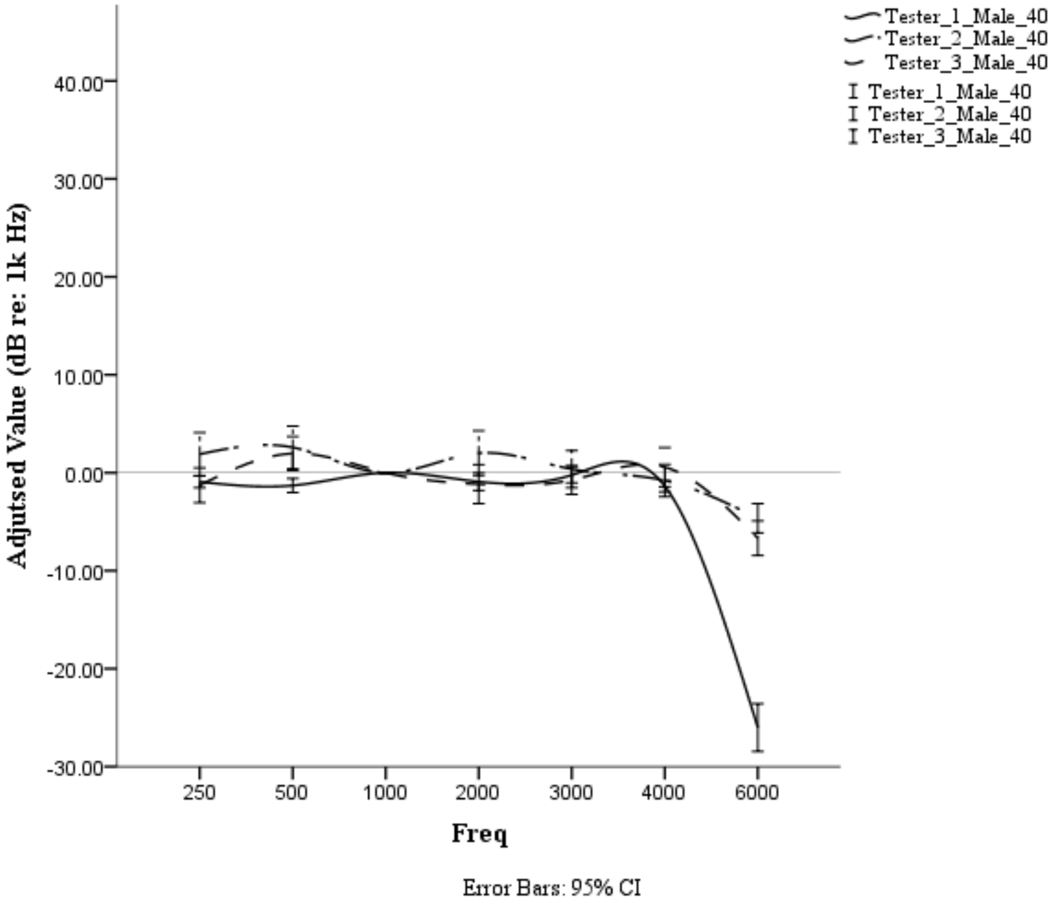

Figure 22. Adjusted mean values for all male participants separated by testers for all bone conduction conditions with a 1000 Hz reference set 40 dB HL.

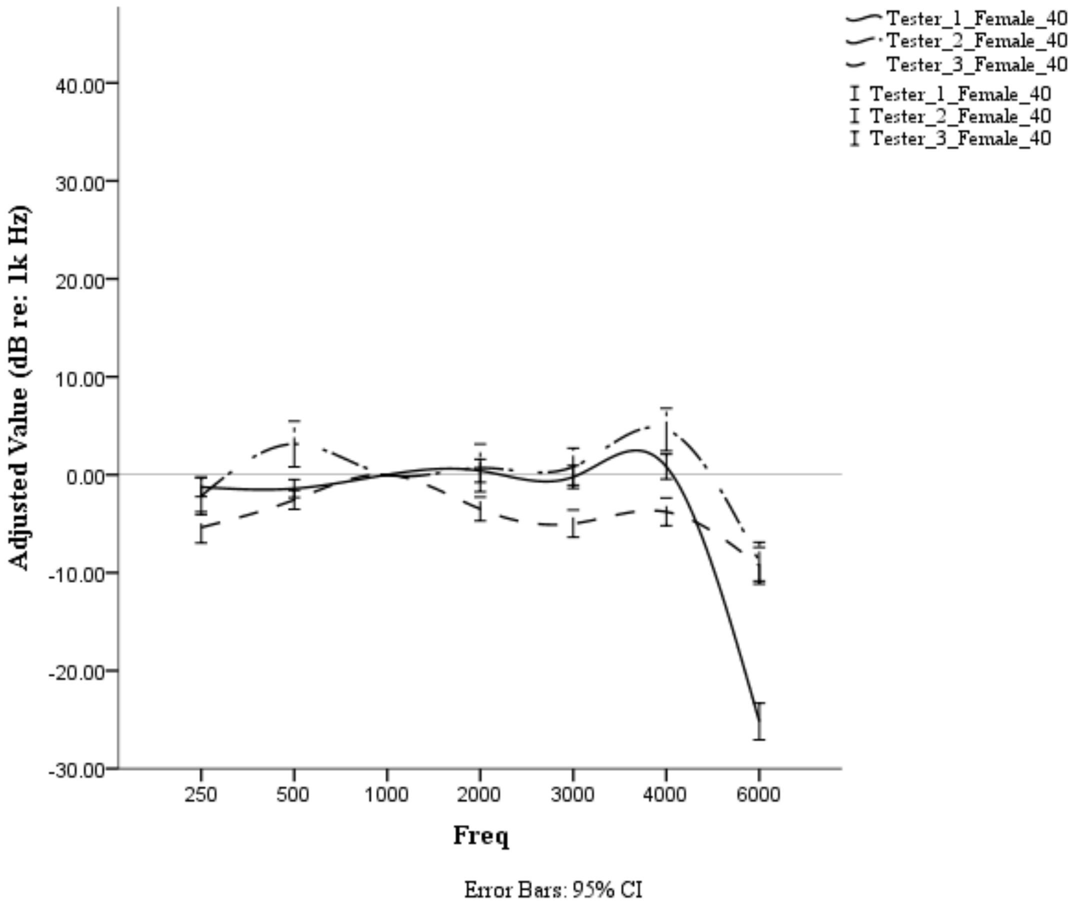

Figure 23. Adjusted mean values for all female participants separated by testers for all bone conduction conditions with a 1000 Hz reference set 40 dB HL.

and by 5-7 dB when compared to tester three. Tester three had lower values at 250, 2000, and 3000 Hz by 2-5 dB when compared to testers one and two.

Figure 24 illustrates a comparison, separated by tester, between male participants averaged across all bone conduction conditions determined with 1000 Hz reference set to20 dB HL. Examination of the figure indicates that tester one had lower values at 250, 500, and 2000 Hz by approximately 2-5 dB when compared to testers two and three. At 3000 Hz, tester one was lower by approximately 10 dB when compared to tester two and by approximately 2 dB when compared to tester three. Tester two was higher at 500 Hz by approximately 2-5 dB and lower by approximately 5-7 dB at 6000 hz when compared to testers one and three.

Figure 25 illustrates a comparison, separated by tester, between female participants averaged across all bone conduction conditions determined with 1000 Hz reference set to 20 dB HL. Examination of figure 25 indicates that tester one was highest at 6000 Hz and tester two was the highest while tester three was the lowest at 3000 HZ. Tester two was higher at 3000 Hz by approximately 5 db when compared to tester one and by approximately 10 dB when compared to tester three. Tester two was lower at 2000 Hz by approximately 2-4 dB at 2000 Hz and 5-7 dB at 4000 Hz when compared to testers one and two.

Statistical analyses were conducted using the SPSS program version 21. The outputs from these analyses are provided in table format throughout this chapter and are summarized in the text.

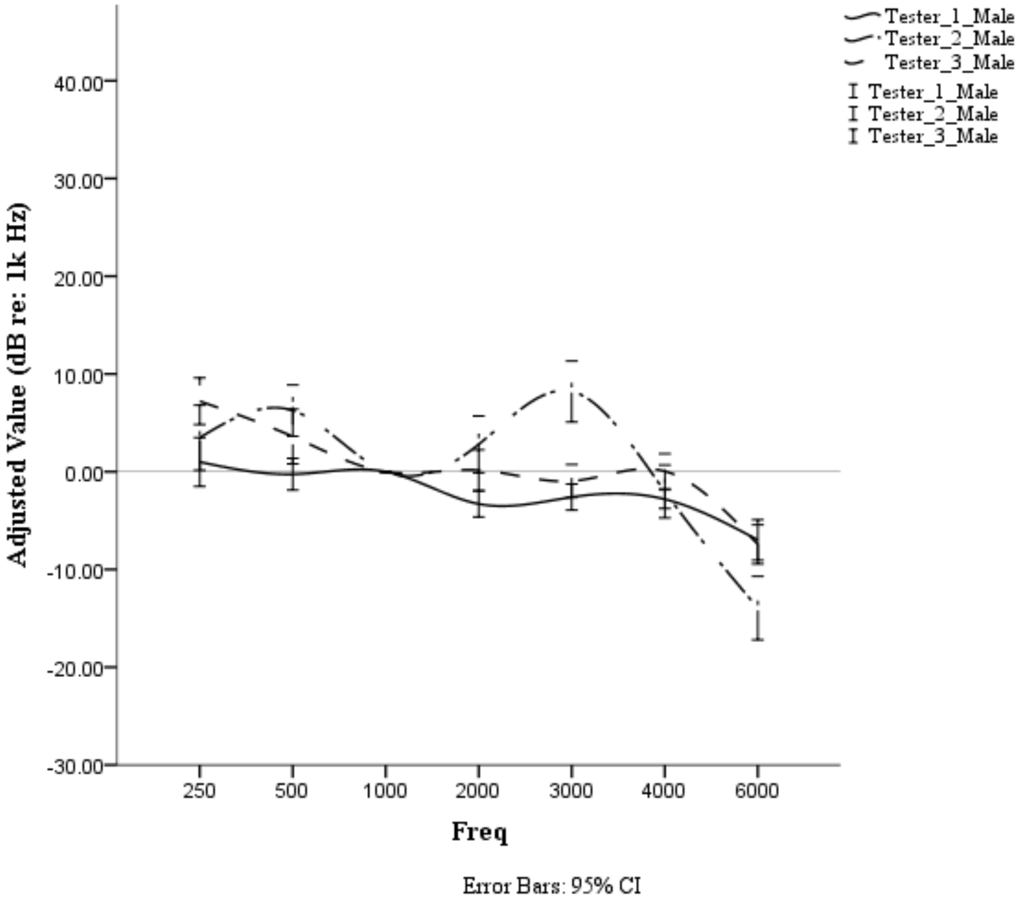

*Figure 24. A*djusted mean values for all male participants separated by testers for all bone conduction conditions with a 1000 Hz reference set 20 dB HL.

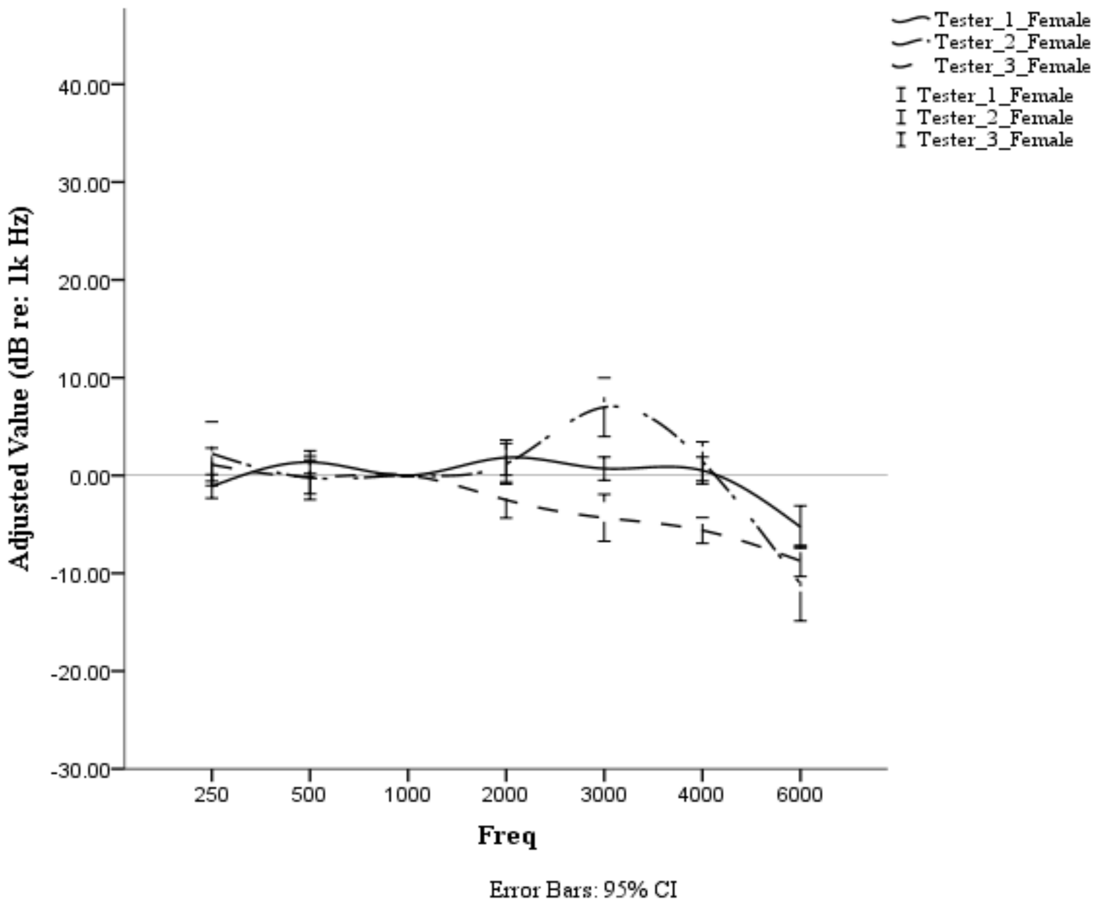

Figure 25. Adjusted mean values for all female participants separated by testers for all bone conduction conditions with a 1000 Hz reference set 20 dB HL.

A 2x2x7 repeated measures ANOVA was used to examine the differences between condition, placement, and frequency at 20 dB HL. The dependent variable is the adjusted mean values and the independent variables are frequency, condition, and placement. Mauchly's test (see Table 1) indicated that the assumption of sphericitiy had been violated, $X^2(20) = 101.420$, $p<.05$; therefore, the degrees of freedom were corrected using Huynh-Feldt estimates of sphericity (e=0.445). Table 2 lists the results of the analysis. In summary, there were no statistically significant differences for condition and placement, $F(1, 29)=1.977$, $p<.05$. Frequency was statistically significant $F(3.175,6) = 23.207$, $p<.05$, $w^2=0.023$ (Table 3).

A 2x2x7 repeated measures ANOVA was used to examine the differences between condition, placement, and frequency at 40 dB HL. The dependent variable is the adjusted mean values and the independent variables are frequency, condition, and placement. Mauchly's test (see Table 4) indicated that the assumption of sphericity had been violated, $X^2(20) = 150.480$, $p<.05$; therefore, the degrees of freedom were corrected using Huynh-Feldt estimates of sphericity (e=0.590). Table 5 and 6 lists the results of the analysis. In summary there were no statistically significant difference for condition and placement, $F(1,29)=26.049$, $p<.05$. Frequency was statistically significant $F(1.983,6) = 41.749$, $p<.05$, $w^2=0.004$.

A 2x2x2x7 repeated measures ANOVA was used to examine the differences between condition, intensity, placement, and frequency. The dependent variable is the adjusted mean values and the independent variables are frequency, condition, intensity and placement. Table 7, 8, and 9 list the results of the analysis. In summary, there were no statistically significant differences for condition and placement, $F(1,29)=13.339$, $p<.05$.

Table 1

Mauchly's Test of Sphericity

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	*df*	Sig.
Frequency	.023	101.420	20	.000
Placement	1.000	.000	0	
Condition	1.000	.000	0	
Frequency*Placement	.116	57.726	20	.000
Frequency*Condition	.087	65.247	20	.000
Placement*Condition	1.000	.000	0	
Frequency*Placement*Condition	.098	62.269	20	.000

Table 2

Tests of Between-Subjects ANOVA

Source	Type III Sum of Squares	*df*	*Mean Square*	*F*	Sig.	Partial Eta Squared
Intercept	250.724	1	250.724	1.977	.170	.064
Error	3678.247	29	126.836			

Table 3

Test of Within-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Frequency	*10337.311	6	1722.885	23.207	.000	.445
	+10337.311	2.836	3645.439	23.207	.000	.445
	×10337.311	3.175	3255.893	23.207	.000	.445
	•10337.311	1.000	10337.311	23.207	.000	.445
Error(Frequency)	*12917.530	174	74.239			
	+12917.530	82.235	157.081			
	×12917.530	92.074	140.296			
	•12917.530	29.000	445.432			
Placement	*56.753	1	56.753	1.531	.226	.050
	+56.753	1.000	56.753	1.531	.226	.050
	×56.753	1.000	56.753	1.531	.226	.050
	•56.753	1.000	56.753	1.531	.226	.050
Error(Placement)	*1074.742	29	37.060			
	+1074.742	29.000	37.060			
	×1074.742	29.000	37.060			
	•1074.742	29.000	37.060			
Condition	*19.458	1	19.458	.393	.536	.013
	+19.458	1.000	19.458	.393	.536	.013
	×19.458	1.000	19.458	.393	.536	.013

	•19.458	1.000	19.458	.393	.536	.013
Error(Condition)	*1437.538	29	49.570			
	+1437.538	29.000	49.570			
	×1437.538	29.000	49.570			
	•1437.538	29.000	49.570			
Frequency * Placement	*77.540	6	12.923	.716	.637	.024
	+77.540	3.388	22.889	.716	.561	.024
	×77.540	3.890	19.933	.716	.579	.024
	•77.540	1.000	77.540	.716	.404	.024
Error(Frequency*Placement)	*3141.802	174	18.056			
	+3141.802	98.243	31.980			
	×3141.802	112.808	27.851			
	•3141.802	29.000	108.338			
Frequency * Condition	*62.989	6	10.498	.577	.748	.020
	+62.989	3.378	18.649	.577	.651	.020
	×62.989	3.877	16.249	.577	.674	.020
	•62.989	1.000	62.989	.577	.453	.020
Error(Frequency*Condition)	*3163.460	174	18.181			
	+3163.460	97.949	32.297			
	×3163.460	112.420	28.140			
	•3163.460	29.000	109.085			
Placement * Condition	*10.483	1	10.483	.222	.641	.008
	+10.483	1.000	10.483	.222	.641	.008

	×10.483	1.000	10.483	.222	.641	.008
	•10.483	1.000	10.483	.222	.641	.008
Error(Placement*Condition)	*1370.161	29	47.247			
	+1370.161	29.000	47.247			
	×1370.161	29.000	47.247			
	•1370.161	29.000	47.247			
Frequency * Placement * Condition	*142.583	6	23.764	1.557	.162	.051
	+142.583	3.307	43.121	1.557	.201	.051
	×142.583	3.783	37.691	1.557	.194	.051
	•142.583	1.000	142.583	1.557	.222	.051
Error(Frequency*Placement*Condition)	*2655.106	174	15.259			
	+2655.106	95.889	27.689			
	×2655.106	109.704	24.202			
	•2655.106	29.000	91.555			

Note: Sphericity assumed is denoted with a * symbol, Greenhouse-Geisser is denoted with a + symbol, Huynh-Feldt is denoted with a × symbol, and Lower-bound is denoted with a • symbol.

Table 4

Mauchly's Test of Sphericity

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	*df*	Sig.
Frequency	.004	150.480	20	.000
Placement	1.000	.000	0	
Condition	1.000	.000	0	
Frequency*Placement	.391	25.130	20	.199
Frequency*Condition	.224	40.006	20	.005
Placement*Condition	1.000	.000	0	
Frequency*Placement*Condition	.389	25.284	20	.194

Table 5

Tests of Between-Subjects Effects

Source	Type III Sum of Squares	*df*	*Mean Square*	*F*	Sig.	Partial Eta Squared
Intercept	3892.753	1	3892.753	26.049	.000	.473
Error	4333.823	29	149.442			

Table 6

Test of Within-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Frequency	*17874.019	6	2979.003	41.749	.000	.590
	+17874.019	1.861	9607.070	41.749	.000	.590
	×17874.019	1.983	9014.029	41.749	.000	.590
	•17874.019	1.000	17874.019	41.749	.000	.590
Error(Frequency)	*12415.795	174	71.355			
	+12415.795	53.955	230.115			
	×12415.795	57.504	215.910			
	•12415.795	29.000	428.131			
Placement	*54.970	1	54.970	1.578	.219	.052
	+54.970	1.000	54.970	1.578	.219	.052
	×54.970	1.000	54.970	1.578	.219	.052
	•54.970	1.000	54.970	1.578	.219	.052

	*1010.529	29	34.846			
	+1010.529	29.000	34.846			
Error(Placement)	×1010.529	29.000	34.846			
	•1010.529	29.000	34.846			
Condition	*87.299	1	87.299	2.368	.135	.075
	+87.299	1.000	87.299	2.368	.135	.075
	×87.299	1.000	87.299	2.368	.135	.075
	•87.299	1.000	87.299	2.368	.135	.075
	*1069.145	29	36.867			
	+1069.145	29.000	36.867			
Error(Condition)	×1069.145	29.000	36.867			
	•1069.145	29.000	36.867			
Frequency * Placement	*32.089	6	5.348	.572	.752	.019
	+32.089	4.686	6.848	.572	.710	.019
	×32.089	5.699	5.630	.572	.744	.019
	•32.089	1.000	32.089	.572	.456	.019
Error	*1627.224	174	9.352			

(Frequency*Placement)	+1627.224	135.890	11.975			
	×1627.224	165.283	9.845			
	•1627.224	29.000	56.111			
Frequency * Condition	*94.006	6	15.668	1.764	.109	.057
	+94.006	3.881	24.225	1.764	.143	.057
	×94.006	4.555	20.639	1.764	.131	.057
	•94.006	1.000	94.006	1.764	.194	.057
Error(Frequency*Condition)	*1545.454	174	8.882			
	+1545.454	112.535	13.733			
	×1545.454	132.090	11.700			
	•1545.454	29.000	53.292			
Placement * Condition	*39.721	1	39.721	.995	.327	.033
	+39.721	1.000	39.721	.995	.327	.033
	×39.721	1.000	39.721	.995	.327	.033
	•39.721	1.000	39.721	.995	.327	.033
Error(Placement*Co	*1157.835	29	39.925			

ndition)	+1157.835	29.000	39.925			
	×1157.835	29.000	39.925			
	•1157.835	29.000	39.925			
Frequency * Placement * Condition	*36.908	6	6.151	.928	.476	.031
	+36.908	4.686	7.876	.928	.461	.031
	×36.908	5.699	6.476	.928	.473	.031
	•36.908	1.000	36.908	.928	.343	.031
Error(Frequency*Placement*Condition)	*1153.507	174	6.629			
	+1153.507	135.888	8.489			
	×1153.507	165.280	6.979			
	•1153.507	29.000	39.776			

Note: Sphericity assumed is denoted with a * symbol, Greenhouse-Geisser is denoted with a + symbol, Huynh-Feldt is denoted with a × symbol, and Lower-bound is denoted with a • symbol.

Table 7

Mauchly's Test of Sphericity

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	*DF*	Sig.
Intensity	1.000	.000	0	
Condition	1.000	.000	0	
Placement	1.000	.000	0	.000
Frequencies	.028	96.048	20	
Intensity*Condition	1.000	.000	0	
Intensity*Placement	1.000	.000	0	
Condition*Placement	1.000	.000	0	
Intensity*Condition*Placement	1.000	.000	0	
Intensity*Frequencies	.001	177.194	20	.000
Condition*Frequencies	.260	36.029	20	.016
Intensity*Condition*Frequencies	.194	43.851	20	.002
Placement*Frequencies	.176	46.568	20	.001
Intensity*Placement*Frequencies	.178	46.214	20	.001
Condition*Placement*Frequencies	.341	28.805	20	.094
Intensity*Condition*Placement*Frequencies	.133	54.030	20	.000

Table 8

Test of Between-Subjects Effects

Source	Type III Sum of Squares	*Df*	*Mean Square*	*F*	Sig.
Intercept	3059.669	1	3059.669	13.339	.001
Error	6651.908	29	229.376		

Table 9

Test of Within-Subjects ANOVA

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intensity	*1083.808	1	1083.808	23.108	.000
	+1083.808	1.000	1083.808	23.108	.000
	×1083.808	1.000	1083.808	23.108	.000
	•1083.808	1.000	1083.808	23.108	.000
Error(Intensity)	*1360.162	29	46.902		
	+1360.162	29.000	46.902		
	×1360.162	29.000	46.902		
	•1360.162	29.000	46.902		
Condition	*3.830	1	3.830	.064	.803
	+3.830	1.000	3.830	.064	.803
	×3.830	1.000	3.830	.064	.803
	•3.830	1.000	3.830	.064	.803
Error(Condition)	*1745.401	29	60.186		
	+1745.401	29.000	60.186		
	×1745.401	29.000	60.186		
	•1745.401	29.000	60.186		
Placement	*2.608	1	2.608	.059	.810
	+2.608	1.000	2.608	.059	.810
	×2.608	1.000	2.608	.059	.810
	•2.608	1.000	2.608	.059	.810

Error(Placement)	*1279.855	29	44.133		
	+1279.855	29.000	44.133		
	×1279.855	29.000	44.133		
	•1279.855	29.000	44.133		
Frequencies	*26506.403	6	4417.734	54.157	.000
	+26506.403	3.201	8279.527	54.157	.000
	×26506.403	3.645	7271.415	54.157	.000
	•26506.403	1.000	26506.403	54.157	.000
Error(Frequencies)	*14193.656	174	81.573		
	+14193.656	92.842	152.880		
	×14193.656	105.713	134.266		
	•14193.656	29.000	489.436		
Intensity * Condition	*126.707	1	126.707	6.064	.020
	+126.707	1.000	126.707	6.064	.020
	×126.707	1.000	126.707	6.064	.020
	•126.707	1.000	126.707	6.064	.020
Error(Intensity*Condition)	*605.968	29	20.895		
	+605.968	29.000	20.895		
	×605.968	29.000	20.895		
	•605.968	29.000	20.895		
Intensity * Placement	*146.413	1	146.413	5.245	.029
	+146.413	1.000	146.413	5.245	.029
	×146.413	1.000	146.413	5.245	.029

	•146.413	1.000	146.413	5.245	.029
Error(Intensity*Placement)	*809.596	29	27.917		
	+809.596	29.000	27.917		
	×809.596	29.000	27.917		
	•809.596	29.000	27.917		
Condition * Placement	*4.696	1	4.696	.078	.782
	+4.696	1.000	4.696	.078	.782
	×4.696	1.000	4.696	.078	.782
	•4.696	1.000	4.696	.078	.782
Error(Condition*Placement)	*1749.284	29	60.320		
	+1749.284	29.000	60.320		
	×1749.284	29.000	60.320		
	•1749.284	29.000	60.320		
Intensity * Condition * Placement	*45.508	1	45.508	1.695	.203
	+45.508	1.000	45.508	1.695	.203
	×45.508	1.000	45.508	1.695	.203
	•45.508	1.000	45.508	1.695	.203
Error(Intensity*Condition*Placement)	*778.712	29	26.852		
	+778.712	29.000	26.852		
	×778.712	29.000	26.852		
	•778.712	29.000	26.852		
Intensity *	*1704.927	6	284.155	4.438	.000
	+1704.927	1.639	1039.922	4.438	.023

Frequencies	×1704.927	1.725	988.628	4.438	.021
	•1704.927	1.000	1704.927	4.438	.044
	*11139.668	174	64.021		
Error(Intensity*Frequencies)	+11139.668	47.545	234.298		
	×11139.668	50.012	222.742		
	•11139.668	29.000	384.126		
	*53.139	6	8.857	.601	.729
Condition * Frequencies	+53.139	3.898	13.632	.601	.658
	×53.139	4.579	11.604	.601	.685
	•53.139	1.000	53.139	.601	.444
	*2564.002	174	14.736		
Error(Condition*Frequencies)	+2564.002	113.049	22.680		
	×2564.002	132.798	19.307		
	•2564.002	29.000	88.414		
Intensity * Condition * Frequencies	*75.297	6	12.549	1.286	.266
	+75.297	4.090	18.410	1.286	.279
	×75.297	4.846	15.539	1.286	.274
	•75.297	1.000	75.297	1.286	.266
	*1698.099	174	9.759		
Error(Intensity*Condition*Frequencies)	+1698.099	118.613	14.316		
	×1698.099	140.522	12.084		
	•1698.099	29.000	58.555		
Placement *	*50.419	6	8.403	.433	.856

Frequencies	+50.419	3.613	13.953	.433	.766
	×50.419	4.191	12.029	.433	.793
	•50.419	1.000	50.419	.433	.516
Error(Placement*Frequencies)	*3377.839	174	19.413		
	+3377.839	104.790	32.234		
	×3377.839	121.548	27.790		
	•3377.839	29.000	116.477		
Intensity * Placement * Frequencies	*26.690	6	4.448	.389	.885
	+26.690	3.783	7.056	.389	.806
	×26.690	4.421	6.037	.389	.834
	•26.690	1.000	26.690	.389	.538
Error(Intensity*Placement*Frequencies)	*1989.134	174	11.432		
	+1989.134	109.704	18.132		
	×1989.134	128.211	15.515		
	•1989.134	29.000	68.591		
Condition * Placement * Frequencies	*52.075	6	8.679	.687	.660
	+52.075	4.528	11.499	.687	.620
	×52.075	5.470	9.520	.687	.647
	•52.075	1.000	52.075	.687	.414
Error(Condition*Placement*Frequencies)	*2196.651	174	12.624		
	+2196.651	131.325	16.727		
	×2196.651	158.623	13.848		
	•2196.651	29.000	75.747		

Intensity * Condition * Placement * Frequencies	*127.416	6	21.236	2.292	.037
	+127.416	3.525	36.150	2.292	.072
	×127.416	4.072	31.290	2.292	.062
	•127.416	1.000	127.416	2.292	.141
Error(Intensity*Condition*Placement*Frequencies)	*1611.962	174	9.264		
	+1611.962	102.214	15.770		
	×1611.962	118.091	13.650		
	•1611.962	29.000	55.585		

Note: Sphericity assumed is denoted with a * symbol, Greenhouse-Geisser is denoted with a + symbol, Huynh-Feldt is denoted with a × symbol, and Lower-bound is denoted with a • symbol.

Chapter 5

Data Analysis and Discussion

This study had three main goals: to compare our study's soundfield equal-loudness contours to published data, to compare loudness levels between soundfield and bone conduction signals, and to create bone conduction equal-loudness contours. Sub-goals included comparisons between placement (mastoid, condyle), laterality (unilateral, bilateral), gender, and intensity level. The results section describes analysis of all of the data. A brief overview of the overall findings is found in the paragraph below. A more in depth discussion will focus on the comparisons between soundfield and bone equal loudness contours and bone conduction equal loudness contours as they relate to mastoid versus condyle placement and intensity effects.

A paired sample t-test was conducted using adjusted mean values to examine differences within the current study's soundfield-to-bone data at each test frequency. The independent variable was frequency and the dependent variable was adjusted mean values. Table 10 and 11 lists the results of the analysis. In summary, statistically significant differences were present at 250 Hz (M=1.9507, SD=4.55809, $t(29)$=2.344, $p<.05$) and 1000 Hz (M=-2.7363, SD=5.15535, $t(29)$=-2.907, $p<.05$) between bone conduction values and the soundfield reference tone.

Recall from the results, that frequency was statistically significant in a 2x2x7 repeated measures ANOVA at both 20 and 40 dB HL reference levels for a 1000 Hz stimulus. However, there were no significant differences found between placements (condyle, mastoid), laterality (unilateral, bilateral) or intensities (20, 40 dB HL) across

Table 10

One-Sample Statistics

Source	N	Mean	Std. Deviation	Std. Error Mean
SB40@250 Hz	30	1.9507	4.55809	.83219
SB40@500 Hz	30	-.0087	4.92348	.89890
SB40@1000 Hz	30	-2.7363	5.15535	.94123
SB40@2000 Hz	30	-1.1060	4.87735	.89048
SB40@3000 Hz	30	-.4333	4.56618	.83367
SB40@4000 Hz	30	-1.5023	4.49311	.82033
SB40@6000 Hz	30	.0477	4.24659	.77532

Table 11

One-Sample Test

Source	*t*	*df*	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the difference
SB40@250 Hz	2.344	29	0.026	1.95067	0.2486,3.6527
SB40@500 Hz	-0.010	29	0.992	-.00867	-1.8471,1.8298
SB40@1000 Hz	-2.907	29	0.007	-2.73633	-4.6614,-.8113
SB40@2000 Hz	-1.242	29	0.224	-1.10600	-2.9272,0.7152
SB40@3000 Hz	-0.520	29	0.607	-.43333	-2.1384,1.2717
SB40@4000 Hz	-1.831	29	0.077	-1.50233	.-3.1801,0.1754
SB40@6000 Hz	1.351	29	0.187	.1.04767	-0.5380,2.6334

test frequencies $p<.05$. Results indicate that laterality, placement, and intensity do not have statistically significant effects on the bone conduction signal.

Comparisons between this study's soundfield-to-bone conduction data and published data from Stenfelt and Hakansson (2002), Patrick et al. (2012), and Pollard et al. (2013) indicated that there should be slight differences between loudness functions between soundfield and bone conduction. In the Stenfelt and Hakansson (2002) study, at an intensity level of 40 dB HL, bone conduction values were 2-3 dB lower than soundfield in the lower frequencies (250-500 Hz) and 1-2 dB lower in the higher frequencies (1000-4000 Hz) when the reference stimulus had an intensity level of 40 dB HL. In the Patrick et al. (2012) study, comparisons were also made between soundfield values and bone conduction values at the mastoid placement at 40 dB SPL. Bone conduction values were 6-7 dB lower than soundfield values in the lower frequencies (250-500 Hz) and 3-7 dB lower in the higher frequencies (1000-4000 Hz). In the Pollard et al. (2013) study, using a reference intensity level of 45 dB SPL, the bone conduction values were 5-15 dB lower than the soundfield in the lower frequencies (250-1000 Hz) and 11-12 dB lower in the higher frequencies (2000-6000 Hz). Comparatively, in our data, bone conduction values were 0-2 dB greater in the low frequencies (250-750 Hz). In the higher frequencies (1000-6000 Hz), bone conduction values were 0-3 dB lower than the air conduction reference value. At the highest frequency tested in our study, 6000 Hz, bone conduction values were greater by 1 dB. The current study data has a pattern in the lower frequencies that does not resemble the pattern from the literature. According to Patrick et al. (2012) and Stenfelt and Hakansson (2002), bone conduction stimulation should need lower intensity to reach equal loudness compared to the soundfield reference stimulus, at all frequencies (Henry & Letowski, 2007). Bone conduction stimulation does not require as much intensity compared to the air conduction stimulus because bone conduction has lower impedance than an air conduction stimulus. Bone conduction transfers a signal directly to the bones of the skull and to the cochlea, which is housed in bone, whereas air conduction transfers a signal through the environment, to the outer ear and into the middle and inner ear causing the signal to attenuate on that path (Henry & Letowski, 2007). In our data, only the mid to high frequency values (1000-6000 Hz) required lower intensity to have equal loudness compared to the soundfield reference tone. In the Stenfelt and Hakansson (2002) and Patrick et al. (2012) study, it was deduced that vibrotactile responses were causing a decrease in bone conduction loudness levels because of increased perception of the loudness of the signal. Additionally, it was hypothesized that the reason the lower frequencies had such lower loudness values compared to soundfield loudness levels was because of the bone transducer producing possible distortion. Once distortion occurred it caused the sound energy to work on a broader range of frequencies, which caused an increase in the loudness level perceived (Patrick et al, 2012).

Patrick et al. (2012), found the forehead placement for the bone vibrator produced the closest approximation to mean loudness levels from the soundfield. Conversely, the condyle location produced mean loudness levels that were furthest from the soundfield mean loudness levels. However, it has been suggested that the condyle placement is most effective to transmit a signal for military application, followed by the mastoid placement (McBride, Letowski, & Tran, 2005). The condyle placement has been judged to be the most effective placement because of the condyle's location, which has been judged to produce vibrations that are effective in auditory stimulation as well as be comfortable for extended wear and with protective head gear (Henry & Letowski, 2007). In the study conducted by Pollard, Tran, and Letowski (2013), comparisons between skull locations indicated that the location most sensitive (had the closest approximation to the air conduction stimulus in soundfield) to bone conduction stimulation was the condyle location compared to the mastoid location. This is in agreement with other studies that have suggested that the mastoid location is best used clinically and the condyle location is best used for communication purposes (Henry & Letowski, 2007). In our study, there were no significant differences found between the mastoid and condyle placement. Further research needs to be done to dictate whether placement does or does not have an effect on the bone conduction signal and whether one placement is superior in transmission of the signal compared to other placements.

There are advantages and disadvantages of both placements used in this study. Physiologically, the mastoid should be the best stimulation site for sound to travel to the cochlea. When the mastoid is used as a bone conduction stimulation site, it causes a vibration of the signal in the horizontal plane that then intersects with the location and position of the cochlea. Conversely, signal vibrations are conducted in the vertical plane when using the forehead as a bone conduction stimulation site. Forehead stimulation allows the signal to get to the cochlea, but not as easily the signal coming from the mastoid as the cochlea is positioned in the horizontal plane (Henry & Letowski, 2007). For the mastoid placement, slight changes in location may cause variability in thresholds, as the vibrator can easily move slightly off the mastoid (Bekesy, 1960). Furthermore, the vibrator is more difficult to secure onto the mastoid location, compared to other placements on the head, because of its rounded surface. However, regardless of the slight instability associated with the mastoid placement, as mentioned earlier, the mastoid placement has been found to produce thresholds that are close to the air conducted thresholds. The mastoid placement also needs less force to reach threshold compared to the forehead placement, which needs an additional 10 dB of force to obtain the same threshold. This is why the mastoid placement is used clinically (Margolis, 2010). Another location that may be used for bone conduction stimulation is the condyle. McBride, Letowski, and Tran (2005) found the condyle location resulted in the lowest thresholds for pure tones, broadband noise, and speech sounds compared to the mastoid and vertex placements. The head placement that produced the lowest thresholds was considered the placement that allowed the best hearing sensitivity. From the study's results it was suggested that the condyle placement be used for transmitting recreational communication (Henry & Letowski, 2007).

It has been suggested that the condyle placement is most effective to transmit a signal for military and recreational communication, because it has been shown to require less force to reach threshold compared with other locations; the mastoid was less effective than the condyle, but more than the forehead placement (McBride, Letowski, & Tran, 2005). From the current study, it seems that either condyle or mastoid placement could be used for transmission of the bone conduction signal. This is consistent with other studies that suggest that a location for bone conduction stimulation is most sensitive when it is coming from the side of the head, which includes the mastoid and condyle placement (Henry & Letowski, 2007).

Chapter 6

Summary and Conclusion

Although it was assumed that values between the soundfield and bone conduction conditions would be similar across all frequencies, loudness is subjective and difficult to judge when two noises are continuously shifting from one transducer to another. Therefore, it is not unlikely that results would change between studies. In the current study, it was found that 250, 1000, and 4000 Hz in the soundfield-to-bone condition, were statistically significantly different from the soundfield reference tone at 40 dB HL. Stenfelt and Hakansson (2002) was the one prior study that had the same intensity level referent (40 dB HL) that was used in the current study (all others used 40 dB SPL or 45 DB SPL); however, contours from the current study did not closely approximate those found by Stenfelt and Hakansson because of a notable deviation in the lower frequencies. Additionally, there were no statistically significant differences observed between the placements, conditions, or intensity of the reference stimulus. Our data seem to suggest that bone conduction communication systems are not affected by placement or laterality; however, this was not true for prior studies. Further research is required to more clearly indicate if the data from the current stuffy can be applied to fitting strategies for bone anchored hearing aids and other bone conduction communication systems.

This is the first study to examine bone conduction equal-loudness contours. The results from this study may provide an additional resource for researchers developing new bone conduction technology and enhancing current devices. For example, BAHA devices are more successful with patients who have a pure tone average of less than 45 dB and therefore the criteria for fitting a BAHA is very limited. This research could help

BAHA manufacturers increase the intensity and frequency range so that the device can be used to fit patients currently outside of the recommended fitting range (Hagr, 2007). Even the BAHA Cordelle which has the ability to fit a severe to profound loss still has limits to its fitting criteria and has a fitting range of 500, 1000, 2000, and 4000 Hz (Bosman, Snik, Mylanus, & Cremersm, 2006). Future research should be done to validate results found in the current study. Future research should consider the use of a bone vibrator with a broader frequency response, such as the B81 vibrator, which has greater output for frequencies below 1000 Hz, and less distortion at frequencies below 1000 Hz (Jasson, Hakansson, Johannsen, & Tengstrand, 2013).

Appendix A

Institutional Review Board and Approval Letter

TOWSON UNIVERSITY

APPROVAL NUMBER: 13-A053

To: David Andreaggi
8000 York Road
Towson MD 21252

From: Institutional Review Board for the Proctection of Human Subjects Justin Buckingham, Member

Date: Monday, April 15, 2013

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

APPROVED
APR 15 2013
TOWSON IRB

Office of University Research Services
Towson University
8000 York Road
Towson, MD 21252-0001
t. 410 704-2236
f. 410 704-4494

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:

Equal Loudness Contours for Bone Conduction and Sound Field Presentation of Frequency-Specific Stimuli at Four Intensity Levels

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: D. Emanuel
File

TOWSON UNIVERSITY

Date: Monday, April 15, 2013

NOTICE OF APPROVAL

TO: David Andreaggi **DEPT:** ASLD

PROJECT TITLE: *Equal Loudness Contours for Bone Conduction and Sound Field Presentation of Frequency-Specific Stimuli at Four Intensity Levels*

SPONSORING AGENCY:

APPROVAL NUMBER: 13-A053

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: 15-Apr-2013
This research will be reviewed every year from the date of first approval.

Amy L Taylor for

Justin Buckingham, Member
Towson University Institutional Review Board

Appendix B

Instructions for the tasks

Soundfield to soundfield:

In this task, the goal is to have the two signals coming from the loudspeaker equal in loudness. The signals will alternate simultaneously. Your job is to notify the tester to turn up or turn down the intensity dial to adjust the volume of one signal, so that it is matching the other in loudness. When you think the signals are the same, notify the tester.

Soundfield to bone:

In this task, the goal is to compare the loudness between the signal coming out of the speaker to the signal coming out of the bone vibrator which you are wearing on your head. Just like the previous task, both signals will be played simultaneously, alternating and you will indicate to the tester to increase or decrease the loudness of the signal from channel 2/adjust the signal coming out of the bone vibrator so it is just as loud as the signal coming out of the speaker. For this task you will be using a method of adjustment technique. Just let me know when you feel that the bone stimuli are just as loud as the soundfield stimuli.

Bone-to-bone:

In this task, the goal is to compare the loudness between two signals coming out of each bone vibrator. Just like the previous task (soundfield-to-bone), both signals will be played simultaneously, alternating and you will have to indicate to the tester to increase or decrease the intensity of the signal in channel 2 and adjust the signal coming out of the bone vibrator so it is just as loud as the reference signal coming out of the other bone vibrator . For this task you will be using the previous method of adjustment technique to adjust the intensity of the bone vibrator stimulus.

Instructions were read to each participant before each task and were given time to digest the instructions and to ask questions.

Appendix C

Calibration and Conversion

Before Testing:

Frequency (Hz)	Bone vibrator/Bone jack (00864)	Bone vibrator/Phone jack (00862)
250 Hz	20 dB HL/70.0 dB SPL	80 dB HL/71.2 dB SPL
500 Hz	20 dB HL/62.1 dB SPL	71 dB HL/62.1 dB SPL
1000 Hz	20 dB HL/46.3 dB SPL	69 dB HL/46 dB SPL
2000 Hz	20 dB HL/41.1 dB SPL	63 dB HL/41.1 dB SPL
3000 Hz	20 dB HL/37.0 dB SPL	70 dB HL/37.0 dB SPL
4000 Hz	20 dB HL/34.2 dB SPL	62 dB HL/33.9 dB SPL
6000 Hz	20 dB HL/38.4 dB SPL	96 dB HL/38.3 dB SPL

250 Hz	40 dB HL/90.1 dB SPL	99 dB HL/90.5 dB SPL
500 Hz	40 dB HL/82.4 dB SPL	91 dB SPL/82.4 dB SPL
1000 Hz	40 dB HL/66.5 dB SPL	89 dB HL/66.1 dB SPL
2000 Hz	40 dB HL/61.1 dB SPL	83 dB HL/61.1 dB SPL
3000 Hz	40 dB HL/57.0 dB SPL	90 dB HL/57.1 dB SPL
4000 Hz	40 dB HL/54.1 dB SPL	82 dB HL/53.9 dB SPL
6000 Hz	40 dB HL/58.6 dB SPL	116 dB HL/58.5 dB SPL

Midway through testing:

Frequency (Hz)	Bone vibrator/Bone jack (00864)	Bone vibrator/Phone jack (00862)
250 Hz	20 dB HL/73.1 dB SPL	80 dB HL/73.5 dB SPL
500 Hz	20 dB HL/66.1 dB SPL	75 dB HL/66.1 dB SPL
1000 Hz	20 dB HL/48.2 dB SPL	70 dB HL/48.6 dB SPL
2000 Hz	20 dB HL/45.5 dB SPL	66 dB HL/45.5 dB SPL
3000 Hz	20 dB HL/40.9 dB SPL	73 dB HL/ 41.0 dB SPL
4000 Hz	20 dB HL/ 36.0 dB SPL	60 dB HL/36.5 dB SPL
6000 Hz	20 dB HL/34.5 dB SPL	85 dB HL/34.4 dB SPL

250 Hz	40 dB HL/93.4 dB SPL	100 dB HL/93.8 dB SPL
500 Hz	40 dB HL/86.5 dB SPL	93 dB HL/86.4 dB SPL
1000 Hz	40 dB HL/68.3 dB SPL	90 dB HL/68.7 dB SPL
2000 Hz	40 dB HL/65.6 dB SPL	86 dB HL/65.6 dB SPL
3000 Hz	40 dB HL/60.9 dB SPL	93 dB HL/61.0 dB SPL
4000 Hz	40 dB HL/56.0 dB SPL	80 dB HL/56.5 dB SPL
6000 Hz	40 dB HL/54.4 dB SPL	105 dB HL/54.5 dB SPL

Appendix D

Two Radio Ear B-71 bone vibrators attached with elastic and Velcro strips

References

Aftershokz open ear sport headphones (2013). *Open Ear Headphones and the Ringing in the Ears Hearing Test.* Retrieved from http://www.aftershokz.com/

American National Standards Institute. (2004b). Sp*ecifications for Audiometers* (ANSI S3.6 – 2004). New York

American National Standards Institute. (2010). *American national standard specification for audiometers* (ANSI 3.6-2010). New York

Amphicom. (2003) Retrieved from: http://www.amphicom.com/pages/produits/indexEN.htm

Banga, R., Lawrence, R., Reid, A., & McDermott, A. (2011). Bone-anchored hearing aids versus conventional hearing aids. *Advances in Oto-Rhino-Laryngology, 71*, 132-139. doi: 10.1159/000323711

Berger, K. W. (1976). Early Bone Conduction Hearing Aid Devices. *Archives of Otolaryngology-Head & Neck Surgery, 102*(5), 315-318. doi:10.1001/archotol.1976.00780100101017

Brandt, A., Håkansson, B., & Stenfelt, S. (2006). Properties of Bone Conduction Hearing. In XXIV International Modal Analysis Conference, St. Louis, Missouri.

Boesen, P. V. (2000)*. U.S. Patent No. 6,094,492* Washington, DC: U.S. Patent and Trademark Office.

Bosman, A. J., Snik, A. F., Mylanus, E. A., & Cremers, C. W. (2006). Fitting range of the baha cordelle. *Int J Audiol.* , *45*(8), 429-437.

British Society of Audiology. (2004). Recommended procedure: Pure tone air and bone conduction threshold audiometry with and without masking and determination of uncomfortable loudness levels. *Br J Audiol*, 1-27.

Christensen, L., Smith-Olinde, L., Kimberlain, J., Richter, G. T., & Dornhoffer, J. L. (2010). Comparison of traditional bone-conduction hearing aids with the BAHA system. *Journal of the American Academy of Audiology, 21*, 267-273.

Cochlear. (2008). Sound. Retrieved from: http://www.cochlear.com/files/assets/corporate/pdf/2008_COH_AR_Editorial.pdf

Elliot, A. M. (2007, August 13). *Hasbro's tooth tunes-musical toothbrushes.* Retrieved from http://www.pocket-lint.com/news/9342/hasbro-tooth-tunes-musical-toothbrushes

Emanuel, D. C., & Letowski, T. (2009). *Hearing science*. (1st ed.). Baltimore: Lippincott Williams & Wilkins.

Feldmann, H. (1997). History of the tuning fork I: Invention of the tuning fork, its course in music and natural sciences. pictures from the history of otorhinolaryngology, presented by instruments from the collection of the Ingolstadt German medical history museum. *Laryngo-Rhino-Otologie, 76*(2), 116-122.

Hagr, A. (2007). Baha: Bone-anchored hearing aid. *International Journal of Health Sciences*, *1*(2), 265-276.

Hakansson, B., Olofsson, M. E., Reifeldt, S., Stenfelt, S., & Granstrom, G. (2008). Percutaneous versus transcutaneous bone conduction implant system: A feasibility study on a cadaver head. *Otology & Neurology, 29(8)*, 1132-1139.

Hakansson, B., Reinfeldt, S., Ostli, P., Taghavi, H., Adler, J., Gabrielsson, J., Stenfelt, S., & Granstrom, G. (2010). A novel bone conduction implant (BCI): Engineering aspects and pre-clinical studies. *International Journal of Audiology, 49*, 203-215.

Henry, P. and Letowski, T. (2007). Bone conduction: Anatomy, physiology, and communication. *ARL Technical Report* ARL-TR-4138. Aberdeen Proving Ground (MD): ARL.

Herstens, T. (2012, March 15). *Aftershokz and TEAC Filltune HP-f100 bone conduction headphones.* Retrieved from http://www.innerfidelity.com/content/aftershokz-and-teac-filltune-hp-f100-bone-conduction-headphones

Hood, J. D. (1962). Bone conduction: A review of the present position with especial reference to the contributions of Dr. Georg von Bekesy. *Journal of Acoustical Society of America, 34*(9B), 1325-332.

International Organization for Standardization (2003). 226: 2003: 'Acoustics-Normal equal loudness-level contours'. *International Organization for Standardization.*

International Organization for Standardization (1994): Acoustics—reference zero for the calibration of audiometric equipment: Part 3: Reference equivalent threshold force levels for pure tones and bone vibrators. *International Organization for Standardization.*

Jansson, K. J., Hakansson, B., Johannsen L., & Tengstrand, T. (2013). A New Audiometric Bone Vibrator-Radioear B81 for more accurate hearing diagnostics. *Department of Signals and Systems, Chalmers University of Technology.*

Retrieved from: http://ortofonmicrotech.com/assets/files/.pdf

Jerger, J., Anthony, L., Jerger, S., & Mauldin, L. (1974). Studies in impedance audiometry: III. Middle ear disorders. *Archives of Otolaryngology—Head & Neck Surgery, 99*(3), 165.

Lightfoot, G. R. (2000). Audiometer calibration: interpreting and applying the standards. *Br J Audiol,* 34, 311-316.

Lightfoot, G. R., & Hughes, J. B. (1993). Bone conduction errors at high frequencies: Implications for clinical and medico-legal implications. *J Laryngol Otol*, *107*(4), 305-308.

Littler, T. S., Knight, J. J., & Strange, P. H. (1952). Hearing by bone conduction and the use of bone-conduction hearing aids. *Proceedings of the Royal Society of Medicine-Otology and Laryngology, 45*(783), 35-43.

Marek, G. R. (1969). *Beethoven: Biography of a genius.* (1st ed.). New York: Funk & Wagnalls.

Margolis, R. H. (2010). A few secrets about bone-conduction testing. *The Hearing Journal*, *63*(2), 10-12.

Maxwell, B. (2011). The Music and Mind of Beethoven: Chords of Disquiet. *CSA Bulletin*, 42.

McBride, M., Letowski, T., & Tran, P. (2005). *Bone conduction head sensitivity mapping: Bone vibrator* (No. ARL-TR-3556). Army Research Lab Aberdeen Proving Ground MD.

McBride, M., Letowski, T., & Tran, P. (2008). Bone conduction reception: Head sensitivity mapping. *Ergonomics, 51*(5), 702 - 718. doi: 10.1080/00140130701747509

Mudry, A., & Tjellstrom, A. (2011). Historical background of bone conduction hearing devices and bone conduction hearing aids. *Advances in Oto-Rhino-Laryngology, 71*, 1-9. doi: 10.1159/000323569

Mylanus, E. A. M., Van der Pouw, K., Snik, A., & Cremers, C. (1998). Intraindividual comparison of the bone-anchored hearing aid and air-conduction hearing aids. *Archives of Otolaryngology-Head & Neck Surgery, 124*, 271-276.

Patrick, R., King, J., McBride, M., & Letowski, T. (2012). Conduction Equivalency ratios: A means for comparing the frequency response of bone and air conduction auditory displays. *Proceedings of the human factors and ergonomics society 56th annual meeting, 56*, 1356-1360. doi: 10.1177/1071181312561389.

Pollack, I. (1952). Loudness of bands noise. *Journal of the Acoustical Society of America, 24,* 533-538.

Pollard, K. A., Tran, P. K., & Letowski, T. R. (2012). A free-field method to calibrate bone conduction transducers. *Journal of Acoustical Society of America, 133*(2), 858-865.

Popelka, G. (2010). Soundbite hearing system by sonitus medical: A new approach to single-sided deafness. *Seminars in Hearing, 31*(4), 393-409.

Stenfelt, S. (1999). *Hearing by bone conduction. physical and physiological aspects.* (Doctoral dissertation), Available from Chalmers Publication Library.

Stenfelt, S., Hakansson, B., & Tjellstrom, A. (2000). Bibration characteristics of bone conducted sound in vitro. *Journal of the Acoustical Society of America, 107*, 422-432.

Stenfelt, S. (2011). Acoustic and physiologic aspects of bone conduction hearing. *Advances in Oto-Rhino-Laryngology, 71*, 10-21. doi: http://dx.doi.org/10.1159/000323574

Stenfelt, S., & Hakansson, B. (2002). Air versus bone conduction: an equal loudness investigation. *Hearing Research, 167*, 1-12.

SwiMP3 2G. (2012). Retrieved from http://www.finisinc.com/swimp3/

Thiagarajan, B. Tuning Fork tests: A review [Internet]. Version 3. ENT Scholar. 2012 Feb 13. Available from: http://entscholar.wordpress.com/article/tuning-fork-tests/.

Tillgren, M. T. (2012). *Growth of loudness for bone conduction.* (Master's thesis).

Toll L.E., Emanuel D.C., Letowski T. (2011): Effect of Static Force on Bone Conduction Hearing Thresholds and Comfort. *International Journal of Audiology* 50:632-635.

Yueh, B., Shapiro, N., MacLean, C. H., & Shekelle, P. G. (2003). Screening and management of adult hearing loss in primary care. *The Journal of the American Medical Association, 289*(15), 1976-85.

Curriculum Vitae

EDUCATION

Towson University: *Towson, MD* Aug. 2011-*Present*
Candidate for Doctorate of Audiology, May 2015

University of Wisconsin-Madison: *Madison, WI* Sept. 2007-May 2011
Bachelor of Arts degree in Communicative Disorders, May 2011

EXPERIENCE

Audiology Extern, May 2013-July 2013
ENTAA Care: Columbia & Glen Burnie, MD
Performed comprehensive audiological evaluations on adults and children.
Administered hearing aid evaluations; programmed, adjusted, and dispensed hearing aids.
Assessed dizziness using Electronystagmography (ENGs).
Evaluated retro-cochlear pathology via Auditory Brainstem Response (ABR) testing

Audiology Extern, Jan. 2013-May 2013
Baltimore County Public Schools: Baltimore, MD
Conducted audiological evaluations and screenings for Pre-K-5 children including pure tone audiometry, immittance, otoscopy, and auditory processing testing.
Wrote reports summarizing results of evaluations and screenings; collaborated with other professionals in IEP meetings to evaluate child's needs.
Maintained and repaired audiologic equipment purchased by school districts.

Audiology Intern, Feb 2012-Dec 2012
Towson University Speech, Language, and Hearing Center: Towson, MD
Completed comprehensive audiological evaluations.
Administered hearing aid evaluations and dispensed hearing aids.
Produced professional reports summarizing audiological evaluation results.

Audiology Intern, Sept. 2010-Dec. 2010
University of Wisconsin Speech and Hearing Clinic: Madison, WI
Performed comprehensive audiological evaluations and generated written findings.