Estimation of the air-bone gap using interleaved air-conduction and bone-conduction ABR

Master of Audiology Thesis

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Abstract

There is a need for monitoring of both the standard and extended frequency range during middle ear surgery. This project set out to provide a system that could receive an estimation of the air-bone gap using interleaved air conduction (AC) and bone conduction (BC) auditory brain-stem response (ABR).

This was accomplished in three different stages. First, two bone conduction transducers were calibrated using the real ear method, Békésy audiometry. Second, three different amplifiers were compared to see which would give the clearest waveforms and be most suitable for the operating theatre. The final stage consisted of testing the system with a normal hearing individual with their ears first unoccluded and then occluded to simulate a conductive loss. A 100 μs click was presented followed by both 4 kHz and 12 kHz tone bursts.

Calibration was done with a focus on the conditions that would be used in surgery, namely the TEAC and B71 occluded and unoccluded with forehead placement. Five participants took part in that part of the study, but the majority of the information came from the student and their primary supervisor.

It was found that a custom fibre optic amplifier (Patuzzi, 2018) would be most suitable for the operating theatre because it is small, battery powered and provides adequate wave forms.

Wave V of the ABR was produced with all three stimuli and the interleaving of the AC and BC. The method created has the potential to provide rapid monitoring of both frequency ranges during middle ear surgery.

Acknowledgments

I would like to express my gratitude for my supervisors, Professor Greg O’Beirne and Dr Alison Cook for their support and guidance throughout the past year. Many hard-worked hours have been put in with software construction, data collection, and analysis. Patients with my inexperience and lack of knowledge in certain aspects of this project is much appreciated and will not be forgotten.

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Chapter 1: Introduction

Middle-ear surgery is often performed to treat conductive hearing loss (CHL) which is manifested in a positive air-bone gap (ABG) on an audiogram. An ABG occurs when there is a significant difference (≥ 15 dB) between the air conduction (AC) thresholds and bone conduction (BC) thresholds and can be caused by a variety of pathologies. Surgeries like stapedectomy, tympanoplasty, mastoidectomy and ossiculoplasty have been shown to improve the ABG within the frequencies of 0.5 – 2 kHz (Doménech & Carulla, 1988; Harder, Jerlvall, Kylen, KylÉN, & Ekvall, 1982). However, there is evidence to show that damage is happening, and thresholds are being affected, causing a temporary threshold shift or even permanent hearing loss. (Antonelli, Gianoli, Lundy, LaRouere, & Kartush, 1998; Bauchet St. Martin, Rubinstein, & Hirsch, 2008; Hegewald et al., 1989; Karatas, Miman, Ozturan, Erdem, & Kalcioglu, 2006; Iain W. S. Mair & Hallmo, 1994; Sutinen, Zou, Hunter, Toppila, & Pyykko, 2007). To limit the adverse effects of middle ear surgery on hearing thresholds, there is a need to monitor these thresholds in real time, during surgery.

Frequencies that are related to speech are most commonly monitored during middle ear surgery, with the definition of success being focused on closing the ABG at said frequencies (Babbage, 2015). Extended high frequencies (EHF) (8-16 kHz) however, are often found to show post-operative deficits. There are many theories on what is causing the EHF hearing loss. For example, Mair and Hallmo (1994) found in their study that the EHF loss was due to changes in the transmission of sound from the middle ear to the cochlea following surgery. Another theory suggests that damage is happening within the cochlea iatrogenically. This means that the drills or lasers used by surgeons are the cause of damage to the cochlea. This has been revealed in pre and post-operative monitoring through pure tone audiometry (Bauchet St. Martin et al., 2008; Hegewald et al., 1989; Karatas et al., 2006; Sutinen et al., 2007). At present, and described in the aforementioned studies, individuals are mostly tested pre-surgery to determine hearing thresholds and then post-surgery to see if there has been any improvement. If there was no or very little improvement, the individuals are scheduled in for revision surgery. There is currently no accepted procedure for monitoring the full frequency range (250 Hz-16 kHz) of humans intraoperatively. To distinguish if the hearing loss is either sensorineural and/or conductive in nature, both AC and BC thresholds would need to be determined rapidly across this frequency range, using an objective procedure such as the auditory brain-stem response (ABR).

There are many challenges that arise when testing the full frequency range using AC and BC ABR during surgery. First, the standard bone conductors (B-71, B-72, and B-81) have not been designed to reach the EHF range without distortion. Therefore, a bone conductor that can perform at these outputs is needed. The TEAC bone transducer has been proposed as a good option for EHF audiometry (Babbage, 2015; Popelka, Telukuntla, & Puria, 2010).

Another challenge is measuring AC thresholds during surgery. This is difficult as earphones can become plugged with fluid, blood, or cerumen. Additionally, in some cases it may not be possible to place the earphones in the external ear canal itself or near the surgical field. Therefore, an alternative way to deliver the AC stimuli must be accomplished. Methods to achieve this using a small free field loud speaker that is flexible enough not to interfere with operating room dynamics will need to be examined.

Furthermore ABR, while being one of the most effective ways of intraoperative monitoring, can be a slow process.(Katz, Chasin, English, Hood, & Tillery, 2015). Getting rapid ABR waveforms is essential in intraoperative monitoring due to time restraints in the operating room. Interleaving the AC and BC stimuli can produce quick and reliable ABR waveforms.

Before progressing to the methods section of this thesis it is important to lay some ground work which will help in the understanding of the topic. Chapter one is an introduction into audiology and its many different facets. A brief understanding of the anatomy and physiology of the auditory system is paramount, along with an idea of how to assess hearing and hearing loss. An introduction to the different types of hearing loss will also be discussed with middle ear pathologies and surgeries used to repair said pathologies. Finally, an introduction to intraoperative ABR will finish off the foundation of knowledge that will aid in the understanding of this thesis.

1.1 Peripheral Auditory System

The peripheral auditory system is commonly separated into three parts; the outer, middle and inner ear (Figure 1). Each part is perfectly designed to transfer sound waves from one's surrounding environment to the brain where those waves are accumulated and perceived as sound. Each part of the peripheral auditory system will be explained in more detail in the following sections.

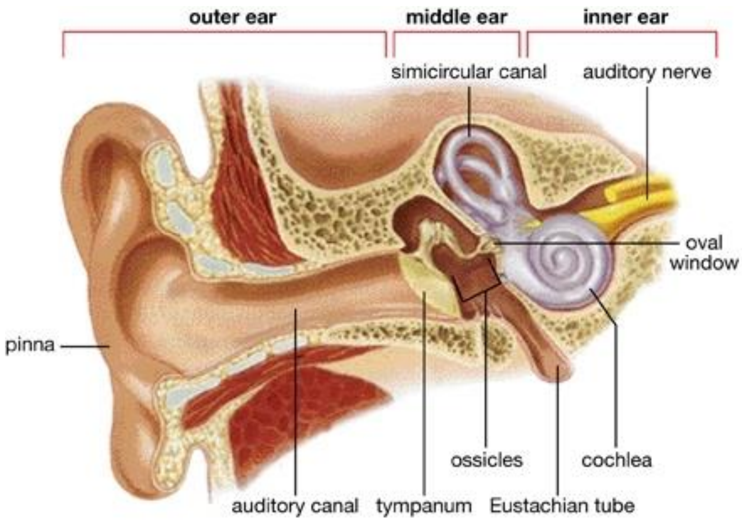


Figure 1: The Peripheral Auditory System (Diagrams, 2018).

1.1.1 The outer ear

The most lateral part of the ear is known as the pinna or auricle. The pinna is made up of a cartilage frame covered in skin and is attached to the head by muscles and ligaments (Babbage, 2015). The pinna's main function is to funnel sound waves down the external auditory canal (EAC) or ear canal to the tympanic membrane (TM). Due to the prominence and shape of the pinna, it also helps in the localization of sound (Batteau, 1967; Hofman & Van Opstal, 2003).

The pinna directs the sound waves down the S-shaped EAC towards the TM. The lateral portion of the EAC is made up of cartilage and covered by a thin epidermal layer, making up approximately one-third of the total length of the ear canal. This cartilage attaches to the bony medial section of the canal which is also lined with skin which is much thinner and doesn't consist of hair follicles and glands as does the lateral portion (Ballachanda, Miyamoto, Miyamoto, & Taylor, 2013). The glands produce cerumen commonly called ear wax which, along with the hair follicles, keep the EAC clean and clear of debris. The total length of the EAC is approximately 25 – 30 mm depending on a person's sex and age. The EAC also has acoustic properties that amplify certain frequencies due to its geometry (Babbage, 2015; Ballachanda et al., 2013; Wiener & Ross, 1946). The most medial bony end of the EAC attaches to the TM.

1.1.2 The middle ear

The tympanic membrane or ear drum is the tissue that divides the outer ear and the middle ear cavity and is the first structure of the middle ear. It is made up of three layers, the lateral consisting of the same thin layer of skin that coats the medial portion of the ear canal. This layer migrates away from the centre of the drum helping with clearing debris and healing damages that may occur (Sharma & Moller, 2006). The medial layer consists of the same mucosal membrane as the middle ear cavity. A connective layer between the medial and lateral layers consists of circular shaped fibres that are more concentrated around the manubrium and extend out to form a ring around the TM. This is where the TM meets the canal wall and forms an attachment (Ballachanda et al., 2013; Møller, 2006; Zemlin, 1998). The TM is oval in shape and slightly concave. It is made up of two areas, the pars flaccida and the pars tensa, the latter taking up the largest portion of the TM and is the point at which it attaches to the manubrium of the malleus (Figure 2).

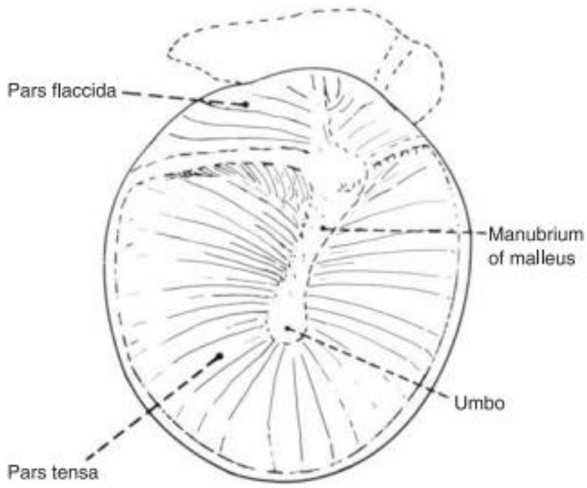


Figure 2: Tympanic Membrane (Sharma & Moller, 2006).

The malleus is one of three bones in the middle ear space or tympanic cavity. It is joined to the incus and the stapes and all three are suspended in the middle ear cavity and attached together by ligaments. These bones are commonly known as the ossicles or the ossicular chain. Their main function is to transfer sound waves from an air to a liquid medium. The stapes is the most medial bone and its footplate sits directly in the oval window. The incus is the largest of the three bones and connects the malleus and stapes. As sound hits the TM, the energy is transferred through the bones to the oval window amplifying it before it enters the inner ear. This amplification is necessary due to the relatively low impedance of air and high impedance of the liquid filled cochlea. The energy transfer happens in three different ways.

The first and most significant is due the size of the ear drum compared to that of the oval window. The TM is approximately 17 times larger than the oval window and therefore the transfer of sound pressure to the cochlea should be approximately 17 times greater than that presented at the TM (Babbage, 2015; Zemlin, 1998). The second mechanism used for sound pressure transfer has to do with the length of the manubrium of the malleus compared to that of the incus' long process. The lever action between these two bones helps increase the energy transfer approximately 1.7 percent. The third and seemingly minute mechanism is the buckling effect of the curved TM (Babbage, 2015; Gelfand, 2016). These mechanisms work together to increase the sound pressure level entering the fluid filled organ of hearing found in the inner ear.

The Eustachian tube is another important structure that is part of the middle ear. The optimal functioning of the middle ear depends on the pressure that is inside it. The pressure should be the same as or close to ambient pressure. This equilibrium is accomplished by the Eustachian tube opening briefly (Sharma & Moller, 2006). Other structures in the middle ear include the smallest muscle in the body, the stapedius muscle, along with the tensor tympani muscle. These muscles are attached to the stapes and the malleus respectively. There main function is to pull these bones away from the TM and oval window to help dampen excessive vibrations or loud sounds entering the cochlea.

1.1.3 The inner ear

The inner ear is made up of a bony labyrinth that is positioned in the temporal bone. The labyrinth is separated into two parts; the vestibular semi-circular canals and the cochlea. For the purpose of this thesis, the cochlea is the only structure that will be discussed.

The cochlea was given its name due to its conical or snail shape. The cochlea has a window-like structure that is covered with a thin film. This is known as the oval window, where the footplate of the stapes sits and transfers vibrations into the cochlea, creating a waveform in the liquid incased therein. This sends a ribbon-like structure called the basilar membrane into motion (Moore, 2012b). The basilar membrane starts at the oval window or the base end of the cochlea, where it is very firm and narrow. It ends at the apex or center of the cochlea, in a wider and more pliable form. The response of the basilar membrane to different frequencies of sound is dependent on its stiffness and width. High frequencies displace the basilar membrane at the base where it is most stiff while low frequencies travel down towards the apex, where the membrane becomes less rigid (Moore, 2012b).The frequency that causes the maximum response by the basilar membrane is known as the characteristic frequency for that specific area (Moore, 2012b). This organization is known as tonotopic mapping (Kamble & Mankar, 2015). Each part of the basilar membrane has corresponding cells called auditory hair cells. There are two types of hair cells in the cochlea known as the outer hair cells (OHC) and the inner hair cells (IHC). They are positioned on the organ of corti which is located on top of the basilar membrane. The OHC's are situated in three or occasionally four rows while the IHC's make up one row. The tectorial membrane which sits on top of the hair cells is where the OHC's stereocilia are embedded. As the tectorial membrane moves in a radial sheering motion, it causes the depolarization of the OHC as potassium enters. As a result, the OHC contracts and elongates. This process is known as electromechanical transduction (Babbage, 2015; Brownell, Bader, Bertrand, & Ribaupierre, 1985; Dallos, 1992). The contraction of the OHC causes greater displacement of the basilar membrane, aiding in the radial sheering of the IHC's stereocilia. Like the OHC's, the IHC's gates are opened, allowing potassium to enter the cell, causing it to depolarize. This process is known as mechanoelectrical transduction. These hair cells then send frequency specific information through transduction to corresponding nerve fibers or afferent neurons. These fibers are bundled together to make up the auditory nerve. The auditory nerve travels through the internal auditory canal adjacent to the facial and vestibular nerves, taking action potentials to the brain stem.

1.2 Central Auditory System

The central auditory system is said to be one of the most complex ascending pathways in the human body (Møller, 2006). An introduction and simple overview of the ascending central auditory system will give a foundation of knowledge needed for understand the auditory brain stem response later in this thesis.

The auditory nerve starts at the organ of corti by directly synapsing mostly to the IHC's. The auditory nerve travels through the inner auditory canal and terminates at the cochlear nucleus (CN) which is in the lower brainstem (Figure 3).

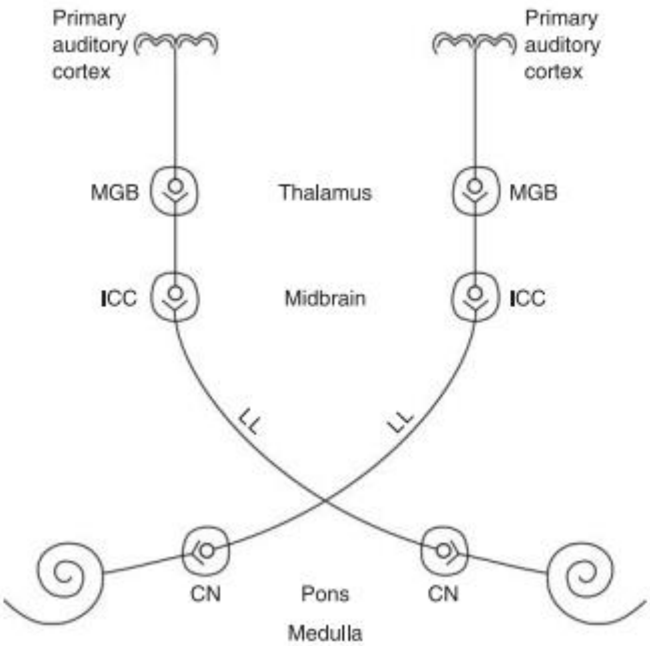


Figure 3: Ascending auditory pathway (Møller, 2006).

The CN is broken up into three parts, the dorsal cochlear nucleus, anteroventral cochlear nucleus, and the posteroventral cochlear nucleus. Each nerve fibre splits and connects to all three sections of the CN which are tonotopically mapped (Katz et al., 2015; Møller, 2006). The next stage in the ascending central auditory system is the superior olivary complex (SOC) which also consists of three subparts, the lateral superior olive nucleus (LSO), medial superior olive nucleus (MSO), and the medial nucleus of the trapezoid body (MNTB). The LSO is made up of high frequency sensitive cells while the MSO's are more sensitive to the lower frequencies (Katz et al., 2015). The SOC is also the first set of nuclei to receive information from both ears and therefore helps interpret directional cues like time, which would be found in the MSO, and intensity, found in the LSO (Katz et al., 2015; Møller, 2006). Both fibres coming from the CN and the SOC make up the Lateral Lemniscus (LL), which travels to either the ipsilateral or contralateral Inferior Colliculus (IC). The IC is located in the midbrain, where all the auditory fibres from the brainstem come together for interpretation. Both, right and left IC's are connected again to help with directionality of sound through interaural time and intensity differences. All the information is then passed through the Medial Geniculate Body (MGB). The MGB is found in the thalamus and can also be separated into three main components; ventral, medial and dorsal nuclei. The IC projects all its information to each part of the MGB (Møller, 2006). The MGB is the last stop before these signals travel to the auditory cortex which is mainly positioned in the temporal lobe. The auditory cortex is a complex network of neurons and it is said that one afferent neuron from the thalamus connects to approximately 5,000 neurons in the cortex (Møller, 2006). The tonotopicity of the human auditory system starts at the basilar membrane and continues through to the primary auditory cortex (Katz et al., 2015).

1.3 Hearing Assessments

There are many tests for adult and paediatric patients that make up a full diagnostic hearing assessment, each being important to help determine the type, degree and configuration of a hearing impairment. For the purposes of this thesis, standard pure tone audiometry, extended high frequency audiometry, Békésy audiometry, tympanometry and electrophysiological assessments will be briefly discussed in this section.

1.3.1 Standard speech frequency audiometry

Pure tone audiometry is the most common diagnostic assessment performed by clinicians. Most clients with a hearing loss express difficulty hearing speech in background noise and therefore the frequencies that are focused on are those in the speech range (0.25 kHz - 8 kHz). Pure tone audiometry is an assessment of hearing thresholds at each specific frequency. A threshold has been defined as the lowest intensity an individual can hear the stimulus, at least 50 percent of the time (Gelfand, 2016; Katz et al., 2015). The hearing thresholds received are then plotted on an audiogram with the decibel hearing level (dB HL) plotted on the y axis and the frequency plotted on the x axis. By doing this, the individual's thresholds can be compared to those of the norms, which indicates weather they have a hearing loss or are within normal limits.

There are two main ways to present a stimulus, one being manually and the other automatically. Manual presentation of a stimulus is most common, where the clinician presents the tones in a specific manner using an audiometer while progressing through the frequency range until the threshold is found. Computer programs can also be used to provide stimuli and progress through the frequency range. Each of these methods depend on the client providing a behavioural response, like pressing a button or raising their hand when they detect the sound. The early procedures of presenting pure tones were time consuming and complex. The modified Hughson-Westlake method is now considered the gold standard and is recommended by ASHA. The sound is presented, then lowered by 10 dB and repeated until the stimulus is no longer heard, following which the sound will be increase by increments of 5 dB until it is heard. The clinician confirms the threshold by receive two repeats at that level (Carhart & Jerger, 1959).

The test stimulus can be presented by air-conduction (AC), bone-conduction (BC) or sound field (SF). In cases of a hearing loss, both AC and BC will need to be tested and compared to determine the type of hearing loss. AC uses the whole auditory pathway by presenting the sound stimulus though headphones placed over the pinna or inserts placed directly in the EAC. Clinicians will usually start in the better ear if a hearing loss is expected or in the right ear if not specified. Bone vibrators like the B-71 or the newer version B-81 by Radioear is used for BC testing which bypasses the outer and middle ear and goes straight into the cochlea (Hakansson, 2003; Jansson, Hakansson, Johannsen, & Tengstrand, 2015). The vibrations of the skull, skin, tendons and liquids in the head cause a traveling wave on the basilar membrane (Khanna, Tonndorf, & Queller, 1976; Stenfelt, Puria, Hato, & Goode, 2003). By bypassing the more peripheral structures of the auditory system, one can determine if there is any pathology associated with those structures. Types of hearing loss and transducers will be discussed in more depth later on.

Placement of the BC transducer is also important to consider while performing pure tone audiometry. There has been a long standing debate on which placement is better, the mastoid or forehead (Studebaker, 1962). The forehead placement has advantages in test-retest reliability and lower variability between subjects (Dirks & Malmquist, 1969; Gelfand, 2016). It is also farther away from the ear than the mastoid and therefore may have less acoustic radiation and effect on the middle ear (Dirks & Malmquist, 1969). These advantages, however, are overlooked due to the more practical placement of the mastoid. For example, the forehead placement needs greater strength to vibrate the cochlea than does the mastoid placement. Therefore, the bone conductor would become vibrotactile at a lower intensity level on the forehead than on the mastoid. Mastoid placement is therefore known to have a wider dynamic range (Babbage, 2015; Dirks & Malmquist, 1969; Gelfand, 2016; McBride, Letowski, & Tran, 2008). This is the major reason why clinicians prefer mastoid placement over the forehead location.

Sound field audiometry is similar to AC in the way that it uses the full auditory pathway. The stimulus is presented through a loudspeaker in a room or space that has been specifically calibrated. The difference and potential down side of sound field audiometry is the lack of ear specific information due to the sound entering both ears (Katz et al., 2015).

Cross-hearing is something to consider while performing audiometry. While the stimulus may be presented in the test ear, if the intensity is loud enough, the other ear or non-test ear can pick up the sound and therefore give false thresholds for the test ear. Due to the energy loss as the sound moves through the head to the non-test ear, there is a corresponding loss in dB. This is known as interaural attenuation (IA). The IA is dependent on frequency and type of transducer used (Studebaker, 1967). For example, it is generally accepted that bone conduction has an IA of 0 dB because the sound is directly transferred though the skull reaching each cochlea with relatively the same energy, and with very little loss (Gelfand, 2016). Furthermore, insert earphones have an IA around 75 dB for 1 kHz and below and 50 dB for those frequencies above 1 kHz (Sklare & Denenberg, 1987). With cross-hearing occurring, masking needs to be applied to find true thresholds of the test ear.

1.3.2 Extended high frequency audiometry

Extended high frequency (EHF) audiometry is rarely performed in a standard audiological assessment. The human auditory system can detect sound up to 20 kHz and the AC testing from 8 kHz to 20 kHz can be done using a standard audiometer and circumaural headphones. However, the frequencies above 16 kHz should be interpreted conservatively due to the poorer test-retest reliability (Babbage, 2015; Frank, 2001; Schmuziger, Probst, & Smurzynski, 2004).

EHF's are usually the first frequencies affected by noise, age and ototoxic drugs (Ahmed et al., 2001; Osterhammel & Osterhammel, 1979; Reuter, Schönfeld, Fischer, & Gross, 1997). Therefore, the monitoring of these frequencies is important and can help with early diagnosis and therefore prevention of a standard speech frequency hearing loss. For example, EHF's are monitored in individuals that are taking medications that are harmful to the auditory system (Beahan, Kei, Driscoll, Charles, & Khan, 2012; schler, vd Hulst, Tange, & Urbanus, 1985; Venter, 2011). If there is a change in the EHF thresholds, there may be adjustments that can be made so that no further loss will occur. This has also been found true with noise-induced hearing loss (NIHL) and acoustic trauma (Ahmed et al., 2001; Büchler, Kompis, & Hotz, 2012; Kiukaanniemi, Lopponen, & Sorri, 1992; Morton & Reynolds, 1991). EHF monitoring is therefore more effective in early prevention of NIHL than that of the conventional 250-8000 Hz.

Even though AC thresholds can be achieved in the EHF range, BC thresholds are not usually tested due to the output of the standard bone conductors and standard audiometers. Babbage (2015) however, used a computer-based audiometer and the TEAC HP-F100 bone-conduction headphones that were modified for audiometric testing to receive accurate BC thresholds for 8 kHz to 16 kHz. By receiving both AC and BC thresholds at EHF's the type of hearing loss can be determined. This is especially important when monitoring individuals that have received middle ear surgery.

1.3.3 Békésy Audiometry

Békésy audiometry was used in this thesis to calibrate the EHF TEAC bone conductor so that it could be reliably used for EHF BC ABR. For this reason, an introduction to Békésy audiometry is discussed.

In the late 1940's, George von Békésy created the first automatic audiometer (Békésy, 1947; Katz, Burkard, & Medwetsky, 2002; Moore, 2012a). This automatic audiometry is also known as self-recorded audiometry where the audiometer plays either a sweeping or constant pure tone frequency. When the tone is heard, the individual performing the test presses a button until the tone is no longer heard and then releases it, and continues in this manner through the full frequency range being tested (Békésy, 1947; Katz et al., 2002; Schmidt et al., 2014). The individual is therefore able to control the intensity of the tone, having it fluctuate closely under and over their threshold. Therefore, the average or mid-point between the responses would be taken as the participant's threshold. This automatic audiometry is seen to be not only more economical due to the lack of skilled operators needed but also more objective as it removes the clinician bias (Schmidt et al., 2014).

1.3.4 Tympanometry

Tympanometry is a standard audiological assessment that helps the clinician understand the current status of the patient's TM and the middle ear space. Tympanometry, otoscopy and pure tone audiometry are all part of the test battery to determine the level of middle ear and Eustachian tube function. An introduction to tympanometry will now be discussed as it was used to help determine who took part in this study.

Tympanometry is a form of acoustic immittance testing, which is a term that refers to both the acoustic impedance (Z_a) and acoustic admittance (Y_a). Acoustic impedance is generally referring to anything that opposes sound flow through the auditory system and admittance is the direct opposite; how easily it flows through the system (Katz et al., 2002). Tympanometry is a measure of acoustic admittance, performed by inserting a probe into the client's ear to create an airtight seal. Once a seal is achieved, an acoustic stimulus or probe tone is presented in the EAC. The presentation of this tone has an accompanying sound pressure level (SPL), which is then measured by a microphone in the probe (Katz et al., 2002). The instrument automatically reads out certain values which are interpreted by the clinician to determine the state of the middle ear. Ear canal volume, admittance or compliance, peak pressure, and tympanic width are all used in the analysis of the tympanogram (Gelfand, 2016; Hamid & Brookler, 2007; Katz et al., 2002). The ear canal volume (Vec) is measured from the probe tip to the TM. This value is used clinically to determine if the TM has perforation or weather there are ventilation tubes, and if they are or are not effective. The admittance or compliance value is taken at the highest point of the tympanogram, or where it reaches the "peak". The peak pressure is the pressure at which the peak of the tympanogram occurs. It is related to the ambient pressure in the room which is presumably 0 daPa. The function of the Eustachian tube is to equalize the middle ear pressure with the ambient pressure. Therefore, this value can indicate if there is a Eustachian tube dysfunction. Tympanic width is found at the half height of the peak and is used clinically to determine whether there is fluid in the middle ear even if a peak is present (Katz et al., 2002). These values contribute to the shape or type of tympanogram. Types "A", "As", "Ad", "Bhigh", "Blow" and "C" are used to characterize the middle ear space and how well it is functioning (Figure 4). Type "A" is a normal tympanogram where the peak pressure is approximately the ambient pressure of 0 daPa. "As" and "Ad" types show shallower or deeper peaks than normal and could indicate hypo or hypermobility of the TM respectively. Type "B" is an abnormal tympanogram where there is no discernible peak and is identified as a flat line on the tympanogram. The admittance is what determines if the type "B" is high or low. A B"" high could indicate be a possible perforation in the ear drum or could be the result of a ventilation tube previously inserted and working as designed. Low admittance is consistent with middle ear effusion, wax occlusion or the probe tip being pushed into the EAC wall (Katz et al., 2015). Type "C" is shown on the tympanogram with a distinctive peak but negative pressure. This result is consistent with Eustachian tube dysfunction as aforementioned.

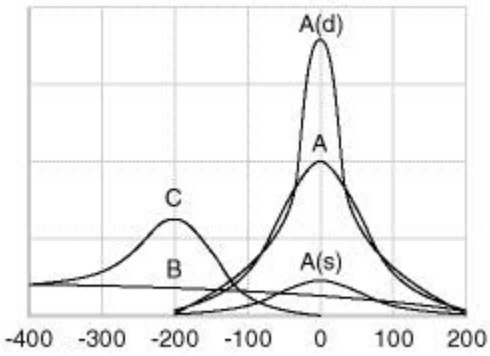


Figure 4: Tympanogram Types (HIMSA, 2015).

Tympanometry is an essential tool used as part of the test battery in diagnosing middle ear pathologies.

1.3.5 Electrophysiological Assessment

As the auditory nervous system is activated by sound stimulus, it elicits electrical signals that can be monitored and measured using specific electrophysiological assessments. These signals are called auditory evoked potentials and are picked up by electrodes that are placed on the head. There are many different electrophysiological assessments used to monitor these evoked potentials; electrocochleography (ECochG), auditory brainstem response (ABR), middle latency response (MLR), auditory steady state response (ASSR) to name a few. Each assessment monitors evoked potentials at different latencies or times along the auditory pathway. For example, ECochG is derived from the electrical signals given by the hair cells in the cochlea and those from the auditory nerve. ABR is produced by the potentials from the auditory nerve and brainstem while MLR is from cortical and subcortical regions (Gelfand, 2016). Though all are interesting and give great insight on how the auditory system works, for the purposes of this thesis, ABR will be the one covered in further detail.

1.3.5.1 Auditory Brainstem Response

ABR is the most common electrophysiological testing technique because it is noninvasive and has been proven to obtain objective hearing thresholds. ABR is described as a short latency response as it records the electrical potentials from the brainstem and auditory nerve. These recordings make up a collection of seven wave forms. These wave forms are seen approximately 10ms after the sound stimuli is presented to the ear (Konrad-Martin et al., 2012). In 1971, Jewett and Williston successfully interpreted these waveforms and eventually gave each wave a corresponding roman numeral from I to VII as show in Figure 5. This system is still used today in the identification of each wave.

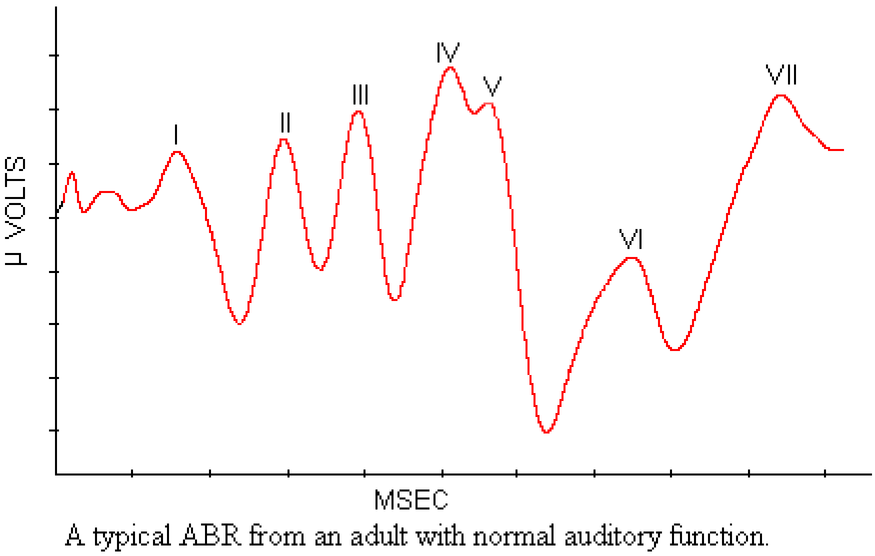


Figure 5: ABR waveforms with identifying roman numerals ("First Years Course 3-Audiology interpretation," 2013).

Each wave or set of waves matches a certain location along the auditory pathway. For example, waves I and II are recorded from the auditory nerve while wave III is created within the cochlear nucleus (Konrad-Martin et al., 2012). Wave V is the most relevant to clinicians, being the largest, and therefore easiest to identify. This is due to the summation of neural activity in the inferior colliculus located in the upper brainstem (Moller, 1999; Picton, 2010). Wave V's latency and amplitude are compared with normative data to identify any abnormalities in hearing thresholds as well as 8th nerve pathologies such as vestibular schwannomas (Lightfoot & Stevens, 2014)

ABR is described as a far field electrophysiological technique due to the distance from where the potentials are evoked and the scalp where they are being measured (Jewett & Williston, 1971). Difficulties can arise and need to be addressed when using far field measurements. The reduction of the signal-to-noise ratio is important for receiving identifiable wave forms. Electrodes are placed on the head in a specific montage, to most effectively measure the electrical potentials of the brainstem (Dzulkarnain, Hadi, & Zakaria, 2013). Electrical and biological interference as well as ambient noise need to be reduced or eliminated to receive reliable data. In some cases, electrical and biological artifacts can enhance wave forms leaving the clinician with false recordings (Atcherson & Stoody, 2012). To reduce the effect of these variables, one should turn off the lights and other electronic devices. Using an electrical shield, like Faraday's Cage, and insulated wires can also go a long way to prevent electrical interference. Furthermore, the individual being tested should be totally relaxed or even asleep to reduce the chance of biological noise such as muscle movement interfering with the recording. Signal averaging of the wave form, the repetition rate of the stimulus and artifact rejection can also increase reliability of results and should be considered while attempting to record ABR (Lightfoot & Stevens, 2014). Due to the far field response, the electrical impulses from the auditory system are extremely small and need proper amplification. This is known as differential amplification and is done through electrode placement on the forehead and mastoid of the test ear (Oshrin & Terrio, 1989). The electrodes and amplifier examine the voltages and amplify what is common to both electrodes and discard the rest (Oshrin & Terrio, 1989). Amplifiers used during ABR are therefore important in receiving clear, robust and accurate wave forms. For this reason, a comparison between different amplifiers will be discussed in more depth later on in this thesis.

The stimulus used to evoke an electrical response is also an important factor when considering the ABR. Click stimuli are the most common because they have a broadband spectrum, meaning that many neurons are firing in synchrony giving a robust waveform when measured at the scalp. This broadband click stimulus however makes it difficult to receive frequency specific information (Gelfand, 2016). The development of the tone burst evoked ABR has made it possible to achieve this frequency specificity. This is done through the rapid raising of intensity before the fundamental frequency, reaching full amplitude at the fundamental frequency and then swiftly dying away. Tone burst ABR is therefore a more practical choice when estimating hearing thresholds in those who cannot perform behavioral audiometry (Gelfand, 2016). Another stimulus has also been found to be effective in the recording of ABR. The rising high frequency chirp stimulus was designed to overcome the time delay along the cochlear partition so that there is even greater synchrony of neural firing (Bargena, 2015; Dau, Wegner, Mellert, & Kollmeier, 2000; Elberling & Don, 2010; Lütkenhöner, 1990; Shore & Nuttall, 1985). This is done by delaying the high frequency component of the stimulus until the lower frequencies reach the apical end of the cochlea. As a result, a greater number of neurons fire at once. The chirp evoked ABR therefore elicits an even larger waveform than the click or tone burst stimuli. This means less averaging, and therefore less time needed to receive objective auditory information. Timely ABR can also be accomplished by interleaving the AC and BC stimuli which will also be discussed further on.

ABR is used by clinicians in multiple aspects of hearing health, from the detection of nerve and brainstem pathologies to identifying hearing thresholds. The most common use of ABR clinically is in newborn hearing assessments as a child cannot give reliable behavioral responses. The importance of early life hearing screening has been well researched and documented (Calcutt, Dornan, Beswick, & Tudehope, 2016; Haghshenas et al., 2014; Pimperton et al., 2016; Stevenson et al., 2011). Early detection and intervention of hearing loss positively influences speech, language, social and learning development outcomes. ABR has been found to be the most effective way in providing this service.

1.3.5.2 Extended High Frequency ABR

Most ABR is done in the standard speech frequencies however, there is a need for receiving objective hearing thresholds in the extending frequency range. For example, high frequency ABR can be used for intraoperative monitoring when ototoxicity is a concern (Fausti, Frey, Henry, Olson, & Schaffer, 1993). A study performed by Fausti et al., examined the latency-intensity functions of both wave I and wave V (Fausti, Olson, Frey, Henry, & Schaffer, 1993). Using tone burst stimuli, 8, 10, 12, and 14 kHz, were tested and the latency of the waves were measured on normal hearing individuals. Wave V was found to be more robust and therefore more reliable in measuring thresholds and latency. The latencies of wave V was around 7 msec. with the expected findings that as the intensity decreases, the latency increases. Fausti et al., also showed that as the frequencies got higher, the latencies increased (1993). Conclusions of this study indicate that extended high frequency air conduction ABR can be accomplished with expected latency-intensity functions (Fausti et al., 1993). This study doesn’t however include the latency-intensity functions for bone conduction ABR and to our knowledge this is still unknown.

1.3.6 Transducers

For any hearing assessment, a device or devices must be used to carry a stimulus to an individual's auditory system. There are many transducers used to provide the stimulus via AC and BC. Both AC and BC transducers will be discussed in this section.

1.3.6.1 Air conduction transducers

The main AC transducers that are used for audiometry are either insert earphones or supra-aural head phones. Inserts have a disposable foam plug that can directly inserted into the EAC. It is attached to the receiver by a long tube. Inserts have many advantages over the supra-aural head phones that make them the optimal choice for hearing assessments. For example, inserts provide an increase in interaural attenuation which reduces the need for masking. Furthermore, they can overcome the risk of collapsing canals that could give erroneous results. Supra-aural headphones have receivers attached to the cushions which sit directly on the pinna. Even though inserts are preferred, supra-aural headphones are convenient, fast and cause less waste. Free field loud speakers that are specifically calibrated can also be used for audiological assessment, however ear specific information is harder to achieve. Circumaural headphones are another type of transducer used for AC. These headphones surround the pinna and are therefore more comfortable and successful in reducing ambient noise. They are also needed in EHF assessment to reach those frequencies above 8 kHz. The supra-aural and circumaural head phones are securely positioned over the ears and held in place by a head band. This band should provide enough force to reach the American National Standards Institute (ANSI) S6-1996 guidelines of 4-5 Newtons (ANSI, 1996; Katz et al., 2002).

1.3.6.2 Bone-conduction transducers

There are many different technologies used to produce BC transducers. The most common for clinical use is the electromagnetic transducer. Radioear has produced three of these transducers, B-71, B-72, B-81 that meet the requirements and recommendations of ANSI (1987) and International Electrotechnical Commission (IEC) (1971). These recommendations include a circular contact tip of 1.75 cm^2 and a static force of 5.4 Newtons against the skull, which is accomplished by the Radioear P-3333 steel sprung headband (Dirks & Kamm, 1975; IEC, 1971).

The B-71 model is the earliest of the three that uses the electromagnetic technology which works on the mass reaction principle, causing a vibration of the skull. Its frequency range is from 250 Hz to 4000 Hz; however, its frequency output is very limited when it comes to anything lower or higher than said frequencies. The total harmonic distortion (THD) levels are fairly high in the lower frequencies restricting the amplitude of the transducer at these frequencies (Dirks & Kamm, 1975; Richards & Frank, 1982).The B-71 is improved upon by the B-72 transducer where the dynamic mass is greater, allowing it to operate at lower frequencies and higher output levels with less distortion (Richards & Frank, 1982). The extra mass and larger transducer however, causes more acoustic radiation or sound leakage at the higher frequencies which can give erroneous threshold results (Bell, Goodsell, & Thornton, 1980; Frank & Crandell, 1986). Clinicians should be aware of these limitations and take appropriate precautions. The most recent BC transducer is the balanced electromagnetic separation transducer (BEST) which works on the balanced suspension principle (Hakansson, 2003). This transducer is commercially available through Radioear and is known as the B-81 transducer. The B-81 further improves the total harmonic distortion at the lower frequencies. The intensity levels are also significantly increased at these lower frequencies using the BEST technology. Though the testing of these lower frequencies is improving, the frequencies above 4 kHz are similar to that of the B-71making it not suitable to test the thresholds in the EHF range (Babbage, 2015; K.-J. F. Jansson et al., 2015).

Another technology used for BC transducers is based on magnetostriction. This is where a flat plate with magnetostrictive properties changes shape when presented with electrical current that creates a magnetic field (Babbage, 2015; Khanna et al., 1976). This type of technology has been proven to push the BC threshold testing into the EHF range (Khanna et al., 1976; Popelka et al., 2010). TEAC has created a transducer, the TEAC HF-100, that is reasonable in size and weight and reliably tests frequencies for 8 kHz to 16 kHz (Babbage, 2015; Popelka et al., 2010). However, the TEAC transducer differs significantly from those Radioear transducers that are ANSI approved for clinical BC testing. For example, the vibrator is convex rather than flat with a diameter much larger than that of the B series (Popelka et al., 2010). Also, due to their commercial use as headphones, the static force applied to the skull does not meet the requirements for clinical use (Babbage, 2015). Babbage (2015) in her study on the effects of middle ear surgery on inner ear function however, modified the TEAC transducer to meet the required static force by removing the plastic standard headband and replacing it with the Radioear P-3333 steel band. The device is shown in before and after modification condition in Figure 6. The same transducer, with its customization used by Babbage (2015) is also used for this current thesis project.

Figure 6: TEAC transducer before and after modification (Babbage, 2015; Popelka et al., 2010).

1.4 Hearing loss

Hearing loss is complex and individual-specific. The causes of hearing loss depend on which structure and mechanism of the auditory system is affected. Hearing loss is identified by type, configuration and degree. There are three main types of hearing loss that will be discussed briefly in this section.

1.4.1 Sensorineural hearing loss

Sensorineural hearing loss (SNHL) is a result of damage or dysfunction of the cochlea and/or other structures further along the pathway, including the auditory nerve, brainstem structures or cortical regions. Most common SNHL's are caused by the damage or death of the OHC's and IHC's, thus limiting the cellular transduction and action potentials firing along the auditory nerve to the brain. In most cases, high frequency losses would be found near the basal end of the cochlea while low frequency losses are towards the apex due to the basilar membrane's tonotopic mapping. Damage to the cochlea causes impairment in areas such as frequency selectivity, loudness perception, pitch perception and auditory sensitivity (Moore, 1996).

SNHL is indicated by AC thresholds and BC thresholds being equal or at least no greater than 10 dB HL apart. Furthermore, the thresholds at any given frequency that are greater than 15 dB HL on the audiogram are considered to be a loss. The greater the dB HL or the farther down you move on the audiogram determines the severity or degree of the loss. As BC audiometry examines the integrity of the cochlea and neural pathways, and AC tests the auditory pathway in its fullness, we can conclude that the loss is generated from the sensorineural structures if the thresholds from each are equal or relatively similar. Presently, SNHL caused by damage to the cochlea and cannot be reversed by surgery.

1.4.2 Conductive hearing loss

Conductive hearing loss (CHL) is due to damage and/or obstruction of the conductive mechanisms in the outer and middle ear. CHL is diagnosed based on a significant, positive air-bone gap (ABG). Due to the fact that AC is evaluating the whole auditory system, we would expect AC thresholds to be greater or elevated compared to those of BC. A positive ABG is considered to be significant if the AC threshold is 15 dB HL greater than the BC threshold at any given frequency. To be considered a solely conductive loss, the BC threshold would have to be within normal limits as indicated on the audiogram (≤15 dB HL). CHL can be chronic or fluctuating making it difficult to assess and treat.

In many cases, CHL can be treated surgically or pharmaceutically. The objective of these treatments is to close the significant ABG. Amplification can also be used to overcome the conductive component if surgery is not an option.

1.4.3 Mixed hearing loss

In the case where both AC and BC thresholds are outside normal limits and a significant ABG is present, a mixed loss would be the diagnoses. The conductive mechanisms and sensorineural structures are therefore pathologic and the decision for rehabilitation should take both into account.

1.5 Middle Ear Pathologies and Surgeries

As mentioned previously, middle ear surgery is a common way to improve AC thresholds and close a significant ABG. The type of surgery as a treatment for middle ear pathologies is highly dependent on the type and degree of hearing loss. The type of surgery used is dependent on which conductive mechanism is affected, how severely it is affected, the preference of the surgeon, as well as many other factors. This section will briefly discuss the surgeries and some of the pathologies they are attempting to remedy. An introduction into how they are performed, and the tools used will also be discussed.

1.5.1 Tympanoplasty

TM perforations are a common middle ear pathology that is caused by trauma or chronic otitis media (COM) (Merchant, Rosowski, & McKenna, 2003). COM is an inflammatory infection that is a result of continual fluid in the middle ear space due to a Eustachian tube dysfunction. Ventilation tubes can be inserted into the TM to help drain this fluid and keep the middle ear dry. In many cases however this is not done, resulting in a perforation of the TM.

Tympanoplasty is an umbrella term used for many surgical reconstruction techniques performed on the TM or middle ear structures (Gelfand, 2016). Myringoplasty for example, is used for smaller perforations where the surgeon will use paper or cartilage as a graft so the existing fibres of the TM can grab a hold and grow in, repairing the perforation (Merchant et al., 2003). For larger perforations, more invasive procedures are needed to elicit lasting results for example; lateral grafts, canaloplasty or total TM replacement (Merchant et al., 2003).

There are two main techniques for TM repair namely, the overlay and underlay technique. The underlay approach however is the most common because it is the easiest to perform (Jung, Kim, Kim, Park, & Martin, 2009). In the underlay technique the graft is placed medially while the overlay technique, the graft is placed laterally to the TM (Jung et al., 2009). Concerning the overlay repair, the ear canal is widened with a drill to reduce the risk of blunting or excess of fibrous growth (Jung et al., 2009; Wang et al., 2011). Both procedures are very successful in repairing TM perforations.

1.5.2 Ossiculoplasty

Ossiculoplasty is a surgical technique used to reconstruct the ossicular chain. This surgery may be done when the ossicles are no longer transferring sound energy effectively from the TM to the inner ear. Ossicular discontinuity, fixation and erosion due to COM or trauma are some ossicular disorders that surgeons attempt to repair using ossiculoplasty. The breakdown of the ossicular chain's transmission function results in a conductive loss, and can be seen as an ABG on the audiogram.

Materials used in these surgeries are dependent on the state of the middle ear and the preference of the surgeon. Autografts, homografts and allografts were the most common prosthetics used when the ossicles were partially eroded or damaged, however in more recent years, allografts have been used less due to the risk of disease (Chavan, Jain, Vedi, Rai, & Kadri, 2014; Fong, Michael, & Raut, 2010). Synthetic prosthetics can also used in cases where there is no ossicular chain or the chain has been extensively damaged. These materials should be easy to manipulate during surgery, biocompatible and stable for optimal results (Seok Moon et al., 2007).

There are two main models used when repairing the ossicular chain. If the stapes superstructure is still intact, partial ossicular reconstruction prosthesis (PORP) is used. When this is not the case, the total ossicular reconstruction prosthesis (TORP) is needed to reconnect the TM to the oval window (Brackmann, Brackmann, Sheehy, & Sheehy, 1979; Fong et al., 2010; Seok Moon et al., 2007; Yu et al., 2013). In the case of fixation, once the problem area is found, a laser or microdrill can be used to divide the fixed structures. The bone or bones, are then removed for reshaping; in cases where an autograft is utilised, or replaced with a prosthetic (Isaacson, Wick, & Hunter, 2017). The PORP and TORP models have been shown to be effective in closing significant ABG's, thereby restoring, or partially restoring, the middle ears function of impedance matching.

1.5.3 Mastoidectomy

Mastoidectomy is the surgical procedure used to remove disease and infection such as COM which could result in a cholesteatoma. A cholesteatoma is a cyst which consists of keratin and cellular debris that continues to grow and encroach on the structures of the middle ear, mastoid and labyrinth (Gelfand, 2016). This type of growth is potentially life threatening and needs to be removed by surgery. Moreover, the primary goal of these surgeries is to remove the pathology while the secondary goal is to preserve or improve hearing (Babbage, 2015; Thiel, Rutka, & Pothier, 2014).

There are three degrees of mastoidectomy; radical, modified radical and simple. Radical mastoidectomy is the total removal of the mastoid and the structures of the middle ear resulting in a rather large conductive hearing loss. The aim of the modified radical surgery is to remove the infectious tissue without taking out the TM and ossicular chain. This surgery penetrates the posterior canal wall, so access can be made to remove the infectious tissue. It is often combined with a tympanoplasty or ossiculoplasty to improve the transfer function of the middle ear. A less damaging surgery is the simple mastoidectomy, where the infection is simply removed from the mastoid without infringing on the middle ear space and EAC (Gelfand, 2016). Drilling and suction are used in combination to remove the infected cells of the mastoid and gain access, if necessary, to the middle ear and EAC.

1.5.4 Stapedectomy/stapedotomy

The final surgical techniques that will be discussed are stapedectomy and stapedotomy. A stapedectomy or stapedotomy may be performed when the stapes is fixated and can no longer perform its’ primary function of transferring sound energy to the oval window. In many cases, the fixation of the stapes is caused by otosclerosis, a remodelling of the bone and/or new bone formation (C. De Souza, Goycoolea, & Sperling, 2014). This otosclerotic material is generally localised and is most likely to affect the oval window and stapes footplate, thus causing its' fixation (Gelfand, 2016). The result is a conductive loss as shown by the ABG on the audiogram. There is also a characteristic notch at 2 kHz where the BC threshold and AC threshold exemplify a sensorineural loss when in fact, it is conductive. This is known as the Carhart's notch and is seen in Figure 7. It is understood that the fixation affects the ocular resonance which is generally around 2 kHz in humans (C. De Souza et al., 2014).

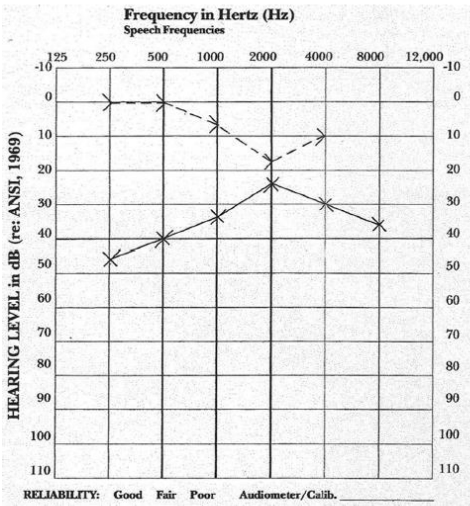


Figure 7: Carhart's notch as seen on an audiogram (C. De Souza, & Kirtane, M.V., 2016).

Inclusion criteria for stapedectomy and stapedotomy surgery are explained by C. De Souza et al. (2014). The BC thresholds should be better than 25 dB HL with the additional criteria being that the AC loss is from 45 to 65 dB HL. The ABG should also be greater than 20 dB HL, if not, the pathology may still be active and growing and/or the hearing impairment not significant enough.

The surgeon first enters by opening the middle ear to access the fixated stapes. Using a laser, the stapes footplate is removed either entirely in cases of stapedectomy and replaced by a prosthesis (Handzel & McKenna, 2010). When a stapedotomy is performed, the footplate is not removed; however, an opening is made in the footplate by pick, drill or laser. The prosthetic is then attached to the incus and placed within the opening to carry the sound energy into the cochlea though the oval window. This procedure is now most common and preferred. (Handzel & McKenna, 2010). Both surgeries however are reliable in closing the ABG and restoring hearing to near normal limits, or to what they were before otosclerosis (Gelfand, 2016).

The frequencies tested to determine the success of these surgeries is in most part those in the speech range (Babbage, 2015). This can be a problem due to the fact that early sensorineural hearing loss is first seen in the EHF range (Ahmed et al., 2001; Osterhammel & Osterhammel, 1979; Reuter, Schönfeld, Fischer, & Gross, 1997). It is therefore important to create clinically acceptable ways to test both AC and BC reliably at these frequencies.

1.6 Hearing Loss Following Middle Ear Surgery

It is well documented that middle ear surgery can cause both temporary and permanent hearing loss in both the speech and EHF range (Babbage, 2015; Goyal, Singh, & Vashishth, 2013; Palva, Karja, & Palva, 1973; Sehra et al., 2018; Smyth, 1977; Somers, Vercruysse, Zarowski, Verstreken, & Offeciers, 2006; Strömberg, Yin, Olofsson, & Duan, 2010). Prevalence, type and potential causes of hearing loss following middle ear surgery will be discussed in this section. A review of EHF's will also be discussed along with its importance in determining damage caused by middle ear surgery to the cochlea.

1.6.1 Prevalence of postoperative hearing loss

It is difficult to determine the prevalence of hearing impairment after middle ear surgery due to the lack of standardised methodology, or the way in which data is reported. For example, one study may use different criteria to determine a loss than that used by another study. Furthermore, each frequency or frequency range is impacted differently and therefore reporting on one but not the other can significantly alter the rates of success or complications. Another factor to consider when determining prevalence of loss post-surgery, is the timing of the postoperative testing. Early postoperative testing may show elevated thresholds, however, in 3 months' time they may be back to normal (Babbage, 2015). It is important to note that these threshold shifts, though temporary, can have adverse effects on cochlear health and hearing later on in life (Sperling, Sury, Gordon, & Cox, 2013). Even though there is high variability following a variety of middle ear surgeries, patients are advised of a 0.6 - 5% chance of permanent hearing loss (Ayache, Lejeune, & Williams; Babbage, 2015; Bergin, 2012; Dawes & Curry, 1974; Lau et al., 1984). This percentage however has been found to go up when considering the higher frequencies (Bauchet St. Martin et al., 2008; Strömbäck et al., 2012). For example, Strömbäck et al. (2012) reported that 6.5% of participants 1 year post surgery for otosclerosis experienced a hearing loss greater than 10 dB at 4, 6 and 8 kHz. Bauchet St. Martin et al. (2008) had similar findings as they reported on adults receiving stapedectomy surgery. Their percentages however were much higher than Strömbäck et al. but this is probably due to the 5 dB versus 10 dB threshold change criteria. In both studies, evidence is given that as the frequency increases, so does the level of hearing loss.

1.6.2 Postoperative extended high frequency hearing loss

The first EHF assessment was performed by Mair and Laukli (1986). Following middle ear surgery they found a significant increase in hearing thresholds from 10 – 16 kHz (I. W. S. Mair & Laukli, 1986). This hearing loss was only found in the extended range leading to the idea that the EHF's are more sensitive to cochlear damage following middle ear surgery. These results were duplicated in other studies, further acknowledging the importance of monitoring the EHF range (Doménech & Carulla, 1988; Tange & Dreschler, 1990). They however, did not receive BC thresholds at those EHF's making it difficult to determine the type of hearing loss presented.

Pre and post monitoring of 22 patients following middle ear surgery using an electromagnetic bone vibrator was done by Mair & Hallmo (1994). They were able to receive both AC and BC masked and unmasked thresholds. The results showed that AC thresholds were slightly elevated while BC thresholds were not significantly changed (Iain W. S. Mair & Hallmo, 1994). The hearing loss therefore was not due to damage to the cochlea, but to the alterations of the structures in the middle ear. In a pilot study conducted by Babbage (2015), 4 participants receiving middle ear surgery were tested pre and postoperatively using Sennheiser HDA 200 circummaural head phones for AC testing and the aforementioned TEAC HP-F100 EHF bone conductor, modified for audiometric use. The postoperative testing was performed 1 week, 1 month and 3 months following surgery to determine longevity of the loss. Two out of the 4 participants in this study showed components of both a conductive and sensorineural hearing losses in the EHF range. The conductive component to the hearing loss was mostly temporary while the SNHL showed a more permanent threshold shift. Babbage (2015) was able to isolate the operated ear, using masking and thereby determined that the SNHL was confined to that ear. This study also concluded that the TEAC transducer was successful in measuring thresholds in the EHF range up to 16 kHz. Though it is small pilot study, it suggests the potential of both temporary and permanent EHF hearing loss following middle ear surgery. It also suggests that both the middle ear and inner ear can be affected by surgical procedures.

1.6.3 Type of loss and their potential causes following middle ear surgery

Determining the type of hearing loss due to middle ear surgery is complex and can be difficult. As indicated in the study by Babbage (2015), sensorineural, conductive, or a combination of these, being a mixed loss, are each possible complications, either temporarily or permanently effecting the patient following middle ear surgery. In this section some of the potential causes of these losses will be discussed.

1.6.3.1 Noise induced hearing loss (SNHL)

Noises produced by drills, lasers and suction during middle ear surgery are at levels that can be detrimental to cochlear hair cells (Hilmi, McKee, Abel, Spielmann, & Hussain, 2012; Kylen, Kylé, n, & Arlinger, 1976; Spencer & Reid, 1985; Strömberg et al., 2010). A general standard known as the 3 dB trading rule for noise exposure has been presented by the National Institute for Occupational Safety and Health (NIOSH) (1998). This rule suggests that as you increase the intensity or loudness of a stimulus by 3 dB, the time it takes for permanent damage to occur is cut in half (NIOSH, 1998). For example, if the intensity is approximately 85 dB. then the time for exposure before damage is 8 hours and if it is at 88 dBA then the time would be cut to 4 hours and so on. This means that permanent threshold shifts can occur in as little time as 30 minutes if the noise level is as high as 96 dBA.

It has been found that airborne noise produced intraoperatively by otologic tools can reach anywhere between 84 -125 dB SPL (Strömberg et al., 2010). Levels in this higher range would cause hearing loss within seconds according to NIOSH's 3 dB trading rule (1998). Airborne noise however is not the only threat for cochlear damage. As the temporal bone is being drilled, there is also potential for hearing loss through the BC pathway. This risk is present in both the ipsilateral and contralateral ear due to the attenuation of BC sound being minimal (Jing Zou, 2001; Kylen et al., 1976; Man & Winerman, 1985). Though the evidence of noise levels produced via the AC and BC pathways during surgery are high and potentially harmful, there is very little evidence to show that it causes significant SNHL. For example, in a study performed by Spenser and Reid (1985), noise produced by the middle ear surgery was high enough to be potentially damaging however, bone conduction audiometry performed 48 hours after the operation showed no evidence of a temporary or permanent shift. They therefore conclude that NIHL after mastoid surgery is unlikely. This however is not to say, that damage cannot occur. Surgeons should take precautions such as limiting the time used in drilling, making sure the drill is operating properly and that the drill burrs are sharp, reducing unnecessary vibrations (Spencer & Reid, 1985).

1.6.3.2 Hydrostatic pressure (SNHL)

As manipulation of the ossicular chain occurs during middle ear surgery, there is a risk of increased hydrostatic pressure applied to the inner ear. The forces exerted on the ossicles during physical manipulation is much greater than those forces that would normally occur physiologically (Babbage, 2015). The normal displacement of the stapes foot plate is very minimal, but during a stapedectomy, the footplate could be displaced up to a millimetre (Schuknecht & Tonndorf, 1960). Palpations of the ossicles by the surgeon, to determine their flexibility and stiffness could also cause the oval window to displace more than it should. This extra force applied to the cochlea increases the stress on the inner ear potentially causing a SNHL.

1.6.3.3 Changes to middle ear Anatomy (Conductive)

The alteration of the middle ear mechanics during middle ear surgeries is another possible cause of threshold shift. For example, the transmission of the sound could be reduced due to the inefficiency of a prosthetic when compared with the original anatomic structure (Murugasu, Puria, & Roberson Jr, 2005; Puria, Kunda, Roberson Jr, & Perkins, 2005). Alterations to the TM can also cause changes in thresholds, especially those in the higher frequencies (Babbage, 2015; O'Connor, Tam, Blevins, & Puria, 2008). For example, when paper is used in a TM repair, it lacks the fibre network of a normal TM. This therefore, can cause the TM to vibrate differently at different frequencies and could be picked up on the audiogram as a hearing loss (O'Connor et al., 2008). The middle ear functions as a complex and finely engineered resonant system. Alterations to any part of this system can change its' ability to perform its' main function of impedance matching.

1.6.4 Conclusion

The middle and inner ear are complex systems and there are many potential causes of hearing loss within middle ear surgery procedures. The ones aforementioned are just a few examples of how middle ear surgery can negatively affect thresholds. For this reason, it is important to be able to monitor hearing thresholds intraoperatively so if they elevate, the surgeon can react in real time either; discontinuing the surgery, attempting to repair damage or alter the procedure for optimal outcomes.

1.7 Intraoperative ABR Monitoring

ABR has been used for intraoperative monitoring for many years. It is a preferred technique for threshold monitoring because it is less invasive, more reliable and stable (Ren et al., 2017). It is well known that intraoperative ABR is being used for monitoring hearing thresholds during neurological surgeries such as the removal of vestibular schwannomas. In 1984, Ojemann and colleagues were some of the first to use ABR for intraoperative monitoring during acoustic neuroma surgery. Having access to real time hearing thresholds allowed the surgeon to be alerted to a potential problem. This led them to make adjustments of the procedure (Ojemann, Levine, Montgomery, & McGaffigan, 1984). Using ABR for middle ear surgery, however, is a relatively new idea and has been of increasing interest to researchers in recent years. For the purpose of this thesis, intraoperative monitoring of middle ear surgery will be reviewed in this section.

1.7.1 Middle ear surgeries

As discussed earlier, there is significant risk of hearing loss both temporarily and permanently post middle ear surgery. Furthermore, revision surgeries are also a risk as success rates decrease as additional surgeries are performed (Hsu, 2011; Lippy, Battista, Berenholz, Schuring, & Burkey, 2003). Aside from this, more problems arise as cost increase, and frustration was felt by both the surgeon and the patient when the revision surgery is required. Revision surgery and potential hearing loss can be reduced by the application of intraoperative ABR.

Selesnick and colleagues performed a study to determine the efficacy of intraoperative ABR for surgery to correct conductive hearing losses (Selesnick, Victor, Tikoo, & Eisenman, 1997). Pure tone audiometry was performed along with speech audiometry pre and post-operation. ABR was performed intraoperatively pre and post-reconstruction and the latencies of wave V were recorded. Significant improvement in the AC, ABG and speech audiometry post-surgery significantly correlated with the decrease in latency of wave V. Selesnick et al. (1997) concluded that the improvement in ABR latencies correlated significantly with post-operation hearing improvements and therefore proved the efficacy of using intraoperative ABR during middle ear surgery.

A more recent study by Hsu (2011) explains the benefits of intraoperative ABR during stapedotomy surgery. 32 patients (34 ears) that had had no previous middle ear pathologies or surgeries were included and received audiograms pre and post-surgery. Click ABR was performed before surgery and after the prosthetics were implanted with the surgeon interpreting the results. Inserts were used, and masking was applied as needed to receive accurate separate ear information. ABR was performed 10 dB higher than each patient's threshold as shown on their audiogram. If wave V was present, the sound intensity was decreased by 10 dB in order to determine new thresholds. In cases where there was no change in thresholds, the prosthetic was repositioned and ABR was run again. 97 % of the patients experienced improved hearing thresholds. 24% of them had the prosthesis manipulated and all showed hearing improvement when tested six weeks post-operation. Hsu (2011) explains that there was no visible indication that the prosthetic was poorly positioned and that the intraoperative ABR was instrumental in the successfully improved hearing results of those 8 patients. Hsu (2011) therefore concludes the importance of intraoperative ABR in stapedotomy surgery, explaining that it can significantly reduce the chance of revision surgery and optimize immediate hearing outcomes.

Another study examined the benefits of intraoperative ABR during myringotomy and tube placement in children with the mean age of 23 months (Sturgill, Yorgason, & Park, 2008). Sturgill et al. (2008) determined that those who were monitored by the intraoperative ABR had illustrated significant improvement in post-operative behavioural testing. However, they cautioned that the presence of middle ear fluid can cause an overestimation of the ABR results, and that it should always be followed up by subsequent behavioural tests (Sturgill et al., 2008).

Using insert ear phones to provide the stimulus for intraoperative monitoring can have its complications. With the presence of fluid, blood and cerumen, the insert can become plugged and cause erroneous results. Another limitation to the previous mentioned studies is the use of clicks for a stimulus. These clicks are not frequency specific as formerly mentioned and generally reflect the 2-4 kHz frequencies (Ren et al., 2017). Ren et al. (2017) noted these limitations and designed a study that would help address them. First, they used a loud speaker to present the stimulus to overcome the limitations of the insert ear phone. Instead of using a click, they utilize the tone pip stimulus which is more frequency specific and closer correlates with thresholds on the audiogram (Frattali et al., 1995; Ren et al., 2017). Normal hearing and conductive loss participants were both tested. Pure tone audiometry was performed with all participants as well as tone pip ABR using the loud speaker. Participants with normal hearing were tested in an audiometric booth and those with the conductive loss were tested in the operating theatre under anaesthesia pre-surgery. Calibration of the system was done prior to the testing to ensure consistent and reliable results. Masking was applied to the contralateral ear to ensure ear specific information. Each participant’s ABR was compared to that of their pre-test 1 kHz threshold found on the audiogram. There was a high correlation between the

ABR results and that of the pre-test audiogram for the conductive loss groups in the operating room. The authors concluded that this ABR monitoring system could work in both the booth and the operating room. This therefore suggests that frequency specific ABR using a speaker is suitable for intraoperative monitoring of middle ear surgery (Ren et al., 2017).

The TEAC magnetostrictive transducer was used in a study to receive ABR from guinea pigs (Bergin, Bird, Vlajkovic, & Thorne, 2015). Bergin et al. (2015) modified the BC transducer by removing the input headphone amplifier so that they could reach frequencies above 24 kHz. The aim of this study was to evaluate the use of the TEAC transducer for ABR and how surgical manipulation of the middle ear would affect cochlear function in guinea pigs (Bergin et al., 2015). In other words, they were attempting to create a mechanism that would give real time EHF thresholds during middle ear surgery. By doing so, the hope is that changes to middle ear surgical procedure will be done to preserve cochlear function. The results of this study show that the TEAC can produce reliable ABR wave forms in the EHF range in guinea pigs. They also found that middle ear manipulation did cause cochlear injury like that found in human subjects. This injury to the basal end of the cochlea effects the higher frequency and is consistent with trauma that is produced by noise (Bergin et al., 2015).

1.8 Aims of Present Study

The benefits of intraoperative ABR monitoring are evident as the literature suggests, however the best way to monitor during middle ear surgery is still being assessed. In the literature just reviewed, there are some limitations that need to be addressed to make intraoperative monitoring more effective. To our knowledge, the existing research around intraoperative ABR for middle ear surgeries does not include interleaved AC and BC stimuli at the speech frequency or EHF range in human subjects. As discussed previously, losses in the EHF range are an early indication of speech frequency hearing loss. EHF hearing loss is also often a complication of middle ear surgery and therefore should be monitored in real time during these operations (Babbage, 2015; Bergin et al., 2015). Both AC and BC should also be included in the monitoring system, so the type of hearing loss can be determined. Achieving ABR for all these frequencies can be difficult with the time limitations in the operating room. Hsu (2011), approximated that the ABR would add another 20 minutes to the surgery which is a significant amount of time especially when not testing the full frequency range. Interleaving the AC and BC stimuli will hopefully provide more rapid ABR wave forms and therefore more frequency specific information, or less time in the operating theatre. Once this is accomplished, surgeons can perform adjustments to the procedure in real time to optimize hearing outcomes long term and reduce the chance of revision surgery.

The aim of this study is to create an intraoperative ABR method in both speech and EHF ranges that will be suitable for middle ear surgery. The study attempts to address the limitations previously discussed. More specifically we aim to provide both AC and BC stimulus in the speech and EHF range. The stimulus will be produced by free field speaker along with both B-71 and TEAC BC transducers. AC and BC will also be interleaved to decrease the time needed to receive the ABR wave forms.

To accomplish these goals, first the TEAC and B-71 transducer need to be calibrated so corrections can be made to ensure accurate hearing thresholds. The methods and results of this task are explained in Chapter 2. As mentioned earlier, amplification of the electrical impulses coming from the auditory system is vital. It is therefore important to compare different amplifiers to see which one will be best suited for our purposes in intraoperative monitoring and gives the clearest wave forms. The comparison of three different amplifiers during ABR is discussed in Chapter 3. When these tasks are complete, we can then test the whole intraoperative monitoring mechanism including, the interleaving of AC and BC stimuli at extended high frequencies. The methods and results of this task will be explained in Chapter 4.

The assumptions made in this study are that the ABG of a normal hearing individual with a type A or Ad tympanogram is 0 dB HL in the standard frequency range and would continue in the EHF range.

2 Chapter 2: Calibration of the TEAC HP-F100/B-71 Transducers

The aim of this phase of the study was to calibrate the TEAC and B-71 transducer for ABR testing, using the real ear method and Békésy audiometry. Furthermore, a comparison of another TEAC transducer was made to ensure they both performed in the same manner. In contrast to traditional audiometry, Békésy audiometry was chosen to enable us to establish biological calibration curves over a continuous, rather than discrete, range of frequencies. A continuous calibration curve would enable tone-bursts to present at known levels, but would also allow the spectrum of broadband stimuli (such as clicks or chirps) to be corrected for the frequency response of the transducer using an inverse filter process.

2.1 Methods

2.1.1 Participants

The participants in this phase of the thesis were the student and both his primary and secondary supervisors. Two additional volunteers also took part in this part of the study. The participants had type "A" tympanograms and normal otoscopic findings. Each participant had measurable hearing thresholds from 250 Hz – 16 kHz. The age range of participants was 23 to 42 years, consisting of three females and two males.

Table 1: Audiometric thresholds (dB HL) for Participants P1 to P5. Measurements for the right and left ears are given for each frequency (Freq).

Freq (Hz)	P1			P2			P3			P4			P5		
	Left	Right	Better	Left	Right	Better	Left	Right	Better	Left	Right	Better	Left	Right	Better
250	-10	-10	-10	0	0	0	0	-5	-5	0	-5	-5	0	0	0
500	-10	-5	-10	-5	-5	-5	0	0	0	-5	0	-5	0	0	0
1k	0	5	0	-5	0	-5	5	5	5	0	-5	-5	0	-5	-5
2k	-10	-10	-10	-10	-5	-10	0	0	0	5	10	5	-5	-5	-5
4k	-10	5	-10	-5	-5	-5	10	10	10	5	0	0	5	-10	-10
6k	-10	5	-10	-5	0	-5	0	5	0	5	10	5	-5	10	-5
8k	10	10	10	5	10	5	15	10	10	15	10	10	10	10	10
9k	-5	-5	-5	0	0	0	10	0	0	5	5	5	-5	0	-5
10k	10	0	0	5	0	0	5	10	5	10	10	10	5	-5	-5
11.2k	5	0	0	0	-5	-5	0	10	0	5	5	5	-5	5	-5
12.5k	-5	0	-5	20	10	10	-5	20	-5	0	0	0	0	-5	-5
14k	5	10	5	50	20	20	15	40	15	5	5	5	-10	5	-10
16k	15	20	15	-	20	20	5	30	5	5	5	5	-5	-10	-10

2.1.2 Materials

Tympanometry was performed with a Clarinet Inventis tympanometer using the 226 Hz probe tone. Pure-tone audiometry was conducted in an audiometric booth at the University of Canterbury. The 250Hz to 16 kHz AC stimuli was presented and generated by the calibrated diagnostic audiometer, GSI 61. TDH-39 supra-aural and Sennheiser HDA 200 circumaural headphones were used for the standard and the EHF range respectively. Bone conduction was presented with the B-71 transducer in the standard .5 to 4 kHz frequency range.

Békésy audiometry was done using a Lenovo Thinkpad laptop with a custom audiometric software developed using LabVIEW seen in Figure 8. The B-71 and TEAC HP-F100 modified by Babbage (2015) were driven by a SoundBlaster X-Fi SBX soundcard, with an NX1 Portable Headphone Amplifier (TOPPING Electronics Technology, Guangzhou, China) providing additional amplification for the B-71, Class 5 foam ear plugs were used to occlude the ear canals to ensure quiet conditions while listen to BC stimuli.

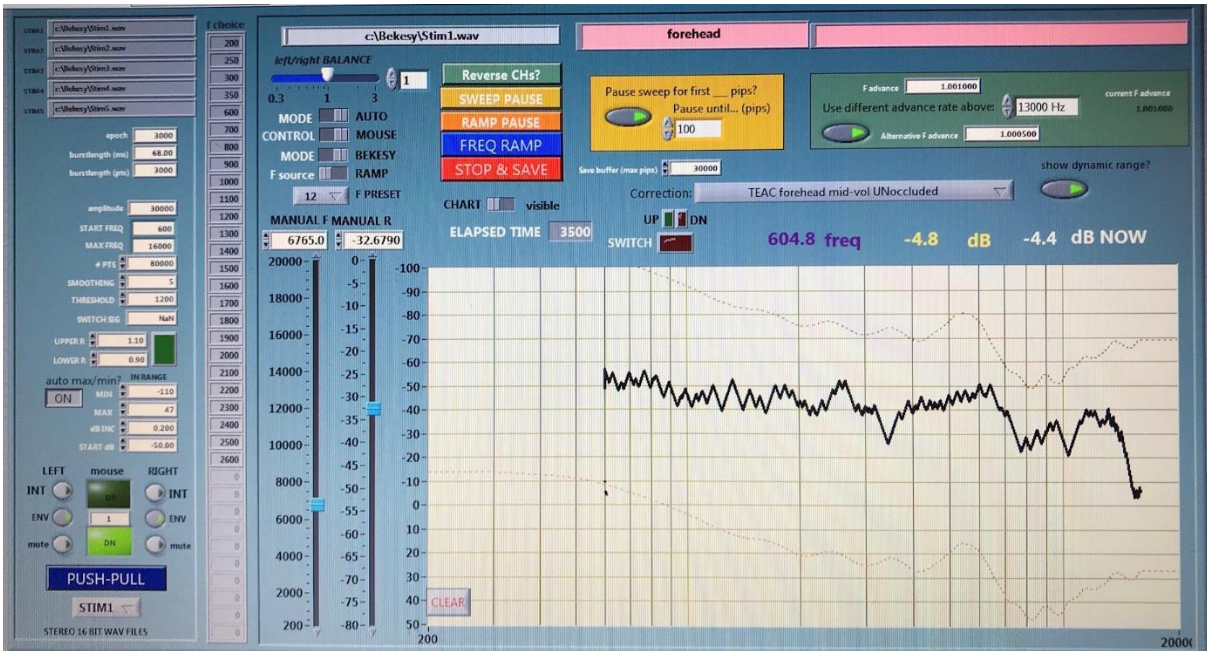


Figure 8: LabVIEW software for Békésy audiometry used in the TEAC calibration, developed by Robert Patuzzi and modified by Alison Cook and Greg O'Beirne (2018).

2.1.3 Procedure

Tympanometry and otoscopy were performed on each participant to ensure clear ear canals and a healthy, fluid free middle ear space. Pure-tone audiometry with a GSI61 audiometer was then performed on all participants using the modified Hughson-Westlake method by a second-year masters of audiology student. Each participant was tested in the audiometric booth to confirm hearing thresholds at the standard and EHF range. AC was tested using the supra-aural headphones for the standard frequency range, up to and including 8 kHz. The EHF range was tested using the Sennheiser HDA200 circumaural headphones from 8 to 16 kHz. Bone conduction was then tested in the standard frequency range with the B-71 bone conductor placed on the mastoid behind the worst ear, to confirm that there was no ABG greater than 15 dB HL or middle ear pathology. Participants were included in this part of the study if there hearing thresholds were measurable at each frequency tested.

Participants were then asked to perform Békésy audiometry using the custom LabVIEW software. Two or more participants were in involved in receiving bone conduction information in eight different conditions. These conditions included either B-71 or TEAC transducers, mastoid or forehead placement and occluded or unoccluded ear canals. Information on how many traces and which participant performed these traces is found in Table 2.

Table 2: Participants and number of traces they completed per condition.

	P1	**P2**	**P3**	**P4**	**P5**
B71 Mastoid occluded	7	5	4	3	1
B71 Mastoid unoccluded	3	0	0	2	0
B71 Forehead occluded*	4	4	3	0	2
B71 Forehead unoccluded*	3	3	0	0	0
TEAC Mastoid occluded	4	3	3	0	1
TEAC Mastoid unoccluded	3	2	0	0	0
TEAC Forehead occluded*	4	3	1	0	0
TEAC Forehead unoccluded*	3	4	0	0	0

The frequency range tested, was from 600 Hz to 16,000 kHz. The frequency was incremented by 0.1% with every stimulus presentation between 600 Hz and 13 kHz, and then by 0.05% from 13 kHz to 16 kHz. The participants were instructed to press the mouse when they heard a sound and stop pressing when the sound was no longer audible. This was to be continued through the whole frequency range.

After the initial data was collected and analysed, a comparison was made between the TEAC transducer at mid volume and at max volume. These traces were then compared to those of the B-71 transducer.

The Békésy data was transferred from the LabVIEW software into an excel spreadsheet for analysis. Full or partial areas of traces were removed from the data set if there were clear lapses in the trace. Signs of the transducer clipping at either the low frequencies or high frequencies were also removed. Therefore, the frequency range of the traces were trimmed, starting at 600 Hz and finishing at 16 kHz.

The nature of Békésy audiometry is that it produces a zig-zag trace that goes above and below threshold, which then lies at approximately the midpoint of the excursions. To smooth this out and to represent the actual threshold a "running average" over the large number of data points (e.g. 90) was done. Given the 3400 data points collected between 600 Hz and 16 kHz, the 90-point smoothing did not overly reduce the frequency resolution of the traces. With 90-point smoothing, each data point was effectively the average over 1/8th octave below 13 kHz, and 1/15th octave above it.

The focus of this thesis is on middle ear surgery and intraoperative monitoring. The traces focused on were therefore, those that would be most applicable to this topic. These included the B71and TEAC transducers placed on the forehead with unoccluded and occluded ear canals. Correction factors were implemented to receive a flatter frequency response of these traces. These corrections were installed into LabVIEW software and new traces were performed to ensure these corrections were working as desired. Due to the time restraints more in-depth exploration of Participant 1 and Participant 2 was focused on.

Participant 1 and Participant 2 are known to have zero air-bone gap due to their Type A tympanometry, and no conductive loss found between 250 Hz and 4 kHz. We therefore assume there would be no ABG above 4 kHz. Furthermore, the AC threshold differences between these two participants would be reflected in BC threshold differences. For example, the 25dB difference in AC hearing thresholds found at 14 kHz (Participant 1 = 5 dB in better ear, Participant 2 = 30 dB in better ear) is cochlear in nature and should therefore produce a 25dB difference in BC thresholds at that frequency. Another assumption is that the transmission of force by the transducer through the skin, tissue and bone is similar between both participants.

Due to only having one TEAC transducer, another one for back up and for a related study was sourced and engineered in the same way as the one from the Babbage study (2015). A comparison was done to verify its performance. One participant was enlisted for this portion of the study who performed many traces of both the old and new transducer.

2.2 Results

To find the output drive to the transducer that would represent 0 dB HL, the hearing thresholds of the participants must be accounted for. For example, if Participant 1's cochlear sensitivity is depressed by 30 dB at 14 kHz, then we can subtract 30 dB from the 14 kHz drive to the transducer to find the drive that would give 0 dB HL in a participant with normal hearing thresholds at that frequency. This is what has been done in the final panels of Figures 9, 10, 11, and 12. Once this correction was established, it was incorporated into the measurement software.

The examples of the calibration given are in the Figures below, using both the B71 and the TEAC transducers on the forehead position, in both the occluded and unoccluded conditions as those are most pertinent to this study.

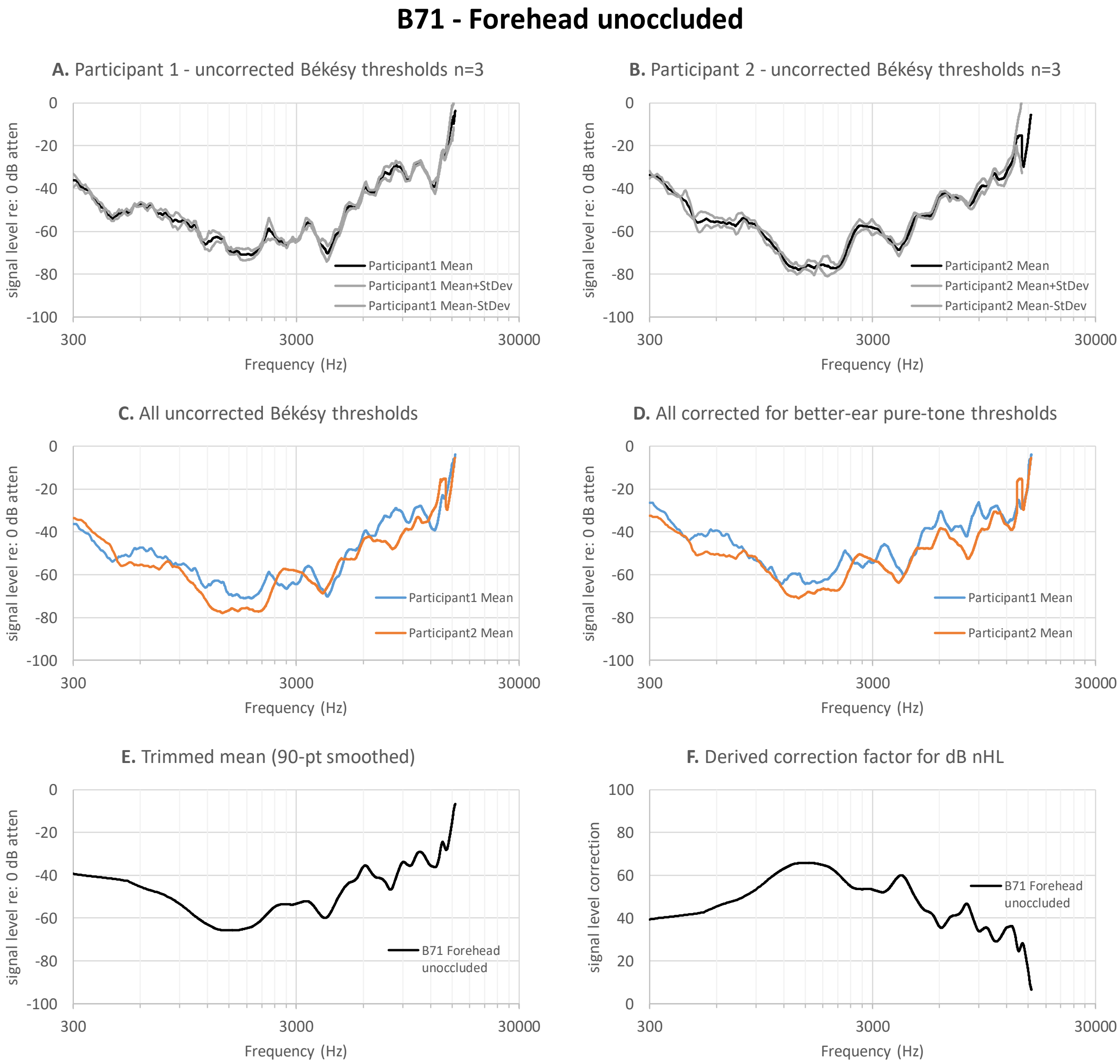


Figure 9: B71 forehead occluded correction traces. A. Participant 1 uncorrected Békésy thresholds with mean. B. Participant 2 uncorrected Békésy thresholds with mean. C. Uncorrected Békésy threshold means of Participant 1 and 2. D. The corrected pure tone threshold means for the better ear of Participant 1 and 2. E. Trimmed and smoothed mean of Participant 1 and 2. F. The correction factor of B71 Forehead unoccluded for dB nHL.

The "trimmed mean" shown in each figure was performed by summing all the traces (e.g. n=6 in Figure 9) and subtracting the minimum and maximum y-value at each x-value. Though this reduces the n by 2, it was found to improve the quality of correction trace by reducing the impact of outlying values. The panels that show "corrected for better-ear pure-tone thresholds" are the result of subtracting each participant's measured AC hearing thresholds (in dB HL) from their BC Békésy traces. The dashed line was the response from

Participant 3 and was eventually omitted from the final correction. The traces were then smoothed by using 90-point smoothing.

If we assume that the AC thresholds for these participants (measured under controlled clinical conditions) are the same as their BC thresholds (i.e. there is no air-bone gap), the correction factors shown in the final panels allow us to determine the participants BC thresholds in something close to dB HL, simply by adding the correction factor to each Békésy trace.

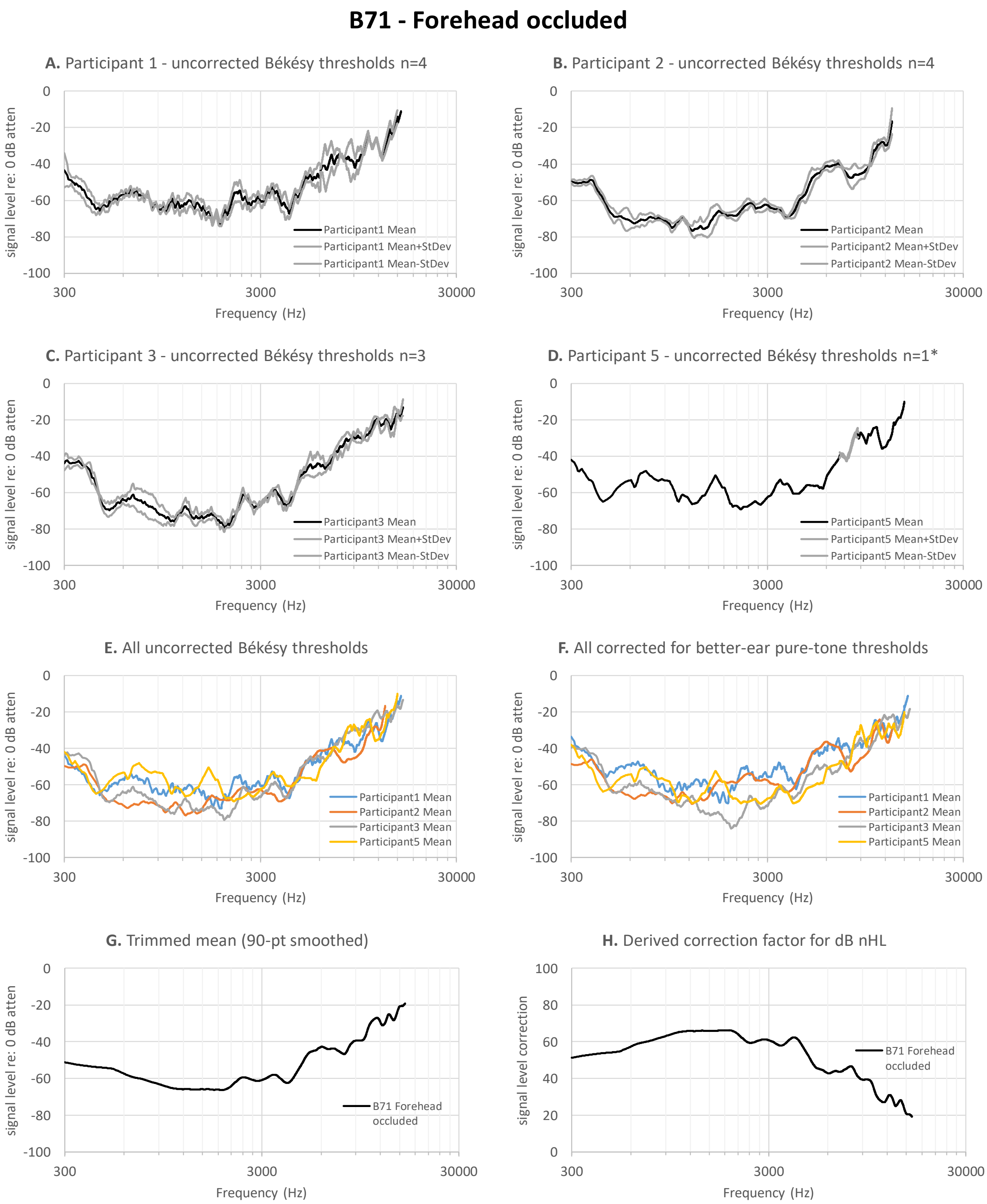


Figure 10: B71 forehead unoccluded correction traces. A-D. Uncorrected Békésy thresholds with their means for Participants 1,2,3,5. E. 5 Participants uncorrected Békésy threshold means. F. 4 Participants corrected pure tone threshold of the better ear. G. Trimmed and smoothed mean of the 4 Participants. H. The correction factor of the B71 Forehead occluded condition for dB nHL.

TEAC - Forehead occluded

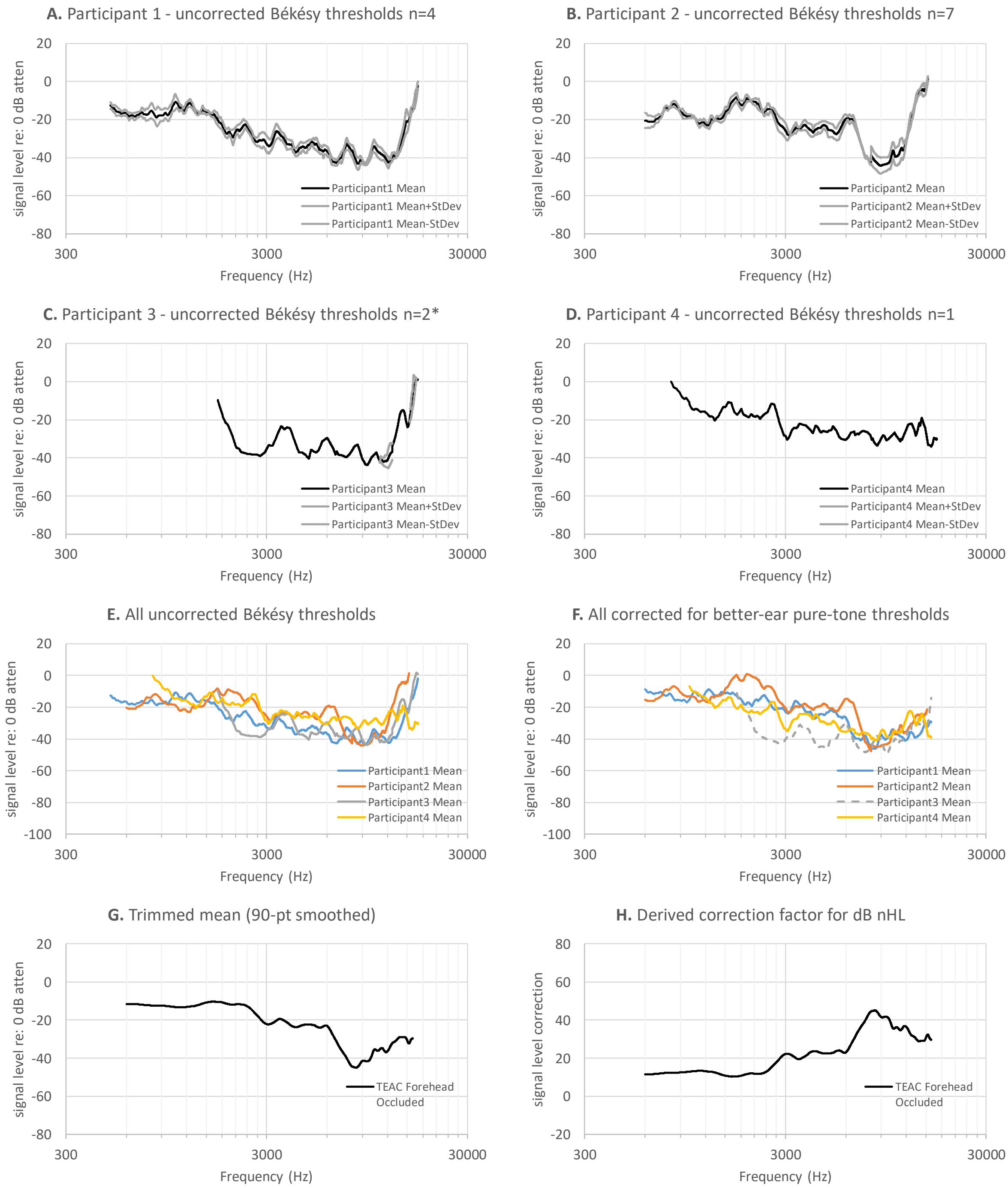


Figure 11: TEAC forehead occluded correction traces. A-D. Uncorrected Békésy thresholds and means of Participants 1-4. E. 4 Participants uncorrected Békésy threshold means. F. 4 Participants corrected pure tone thresholds in the better ear. The dashed line seen in panel F. was the response from Participant 3, which was eventually omitted from the final correction. G. Trimmed and smoothed mean of the 3 remaining Participants. H. The correction factor of the TEAC forehead occluded for dB nHL.

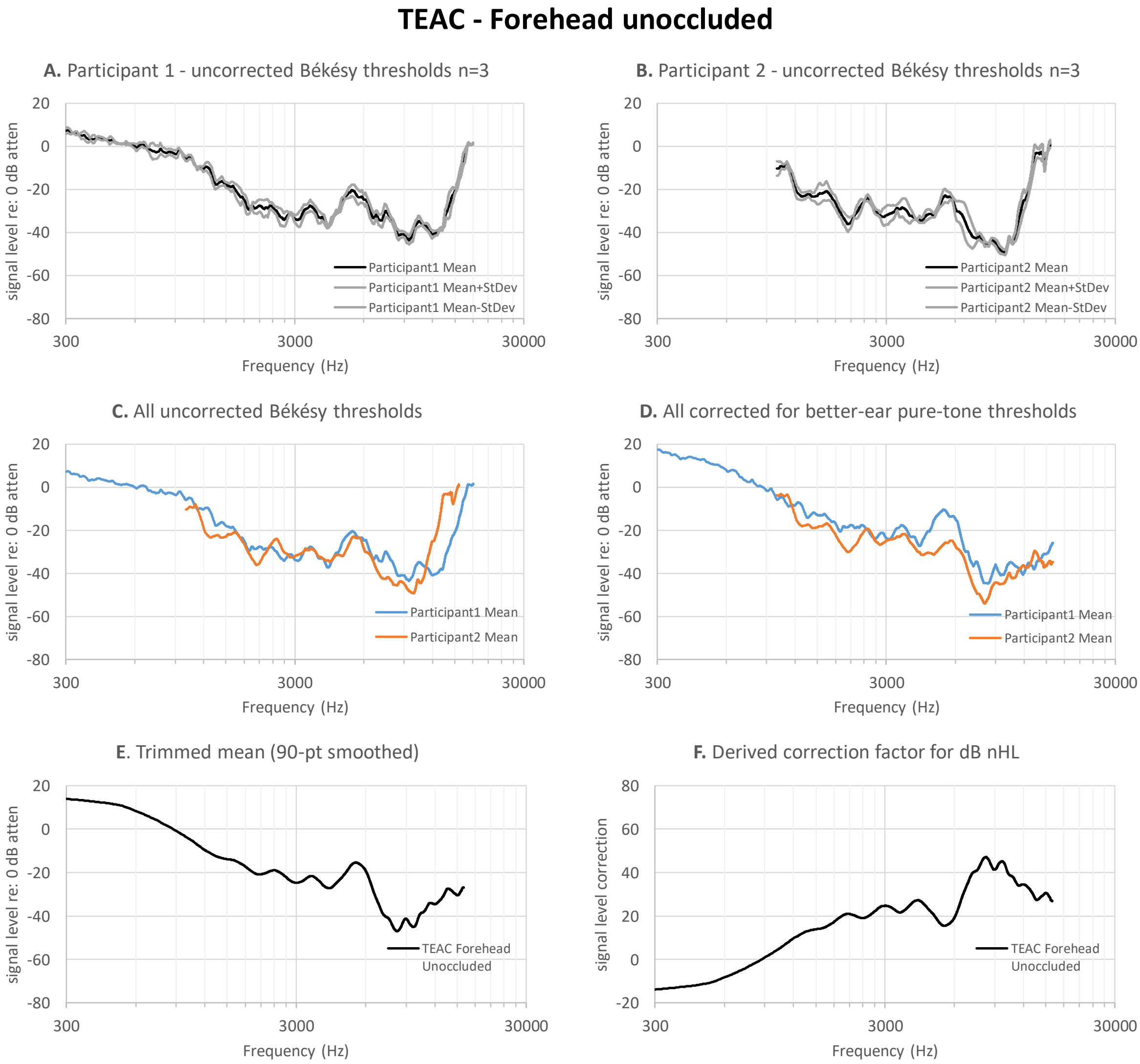


Figure 12: TEAC forehead unoccluded correction traces. A. Participant 1 uncorrected Békésy thresholds with mean. B. Participant 2 uncorrected Békésy thresholds with mean. C. Uncorrected Békésy threshold means of Participant 1 and 2. D. The corrected pure tone threshold means for the better ear of Participant 1 and 2. E. Trimmed and smoothed mean of Participant 1 and 2. F. The correction factor of TEAC Forehead unoccluded for dB nHL.

These findings show a somewhat limited dynamic range of the TEAC device. At “maximum volume” or high gain, the device gives a higher output level, however, as shown in Figure 13 it increases the noise floor and therefore limits perception of the lower level sounds. When the volume is set at a moderate “mid-volume” gain setting, it allows for more accurate determination of psychophysical threshold, but reduces maximum output level.

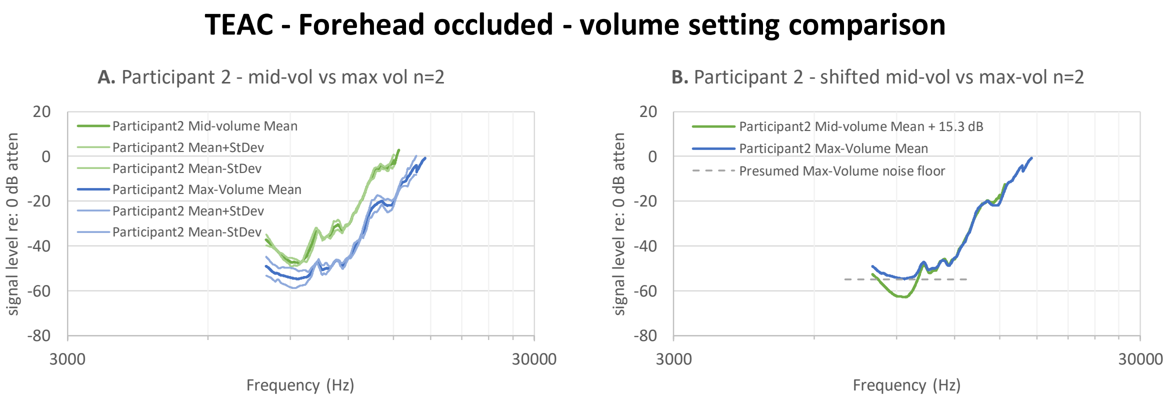


Figure 13: A. Comparison of volume settings for the TEAC bone conductor in the forehead occluded condition over the high-frequency range (8 kHz to 16 kHz). B. The curves closely overlie when the mid-volume trace is shifted by 15.3 dB, except that the max-volume threshold trace (in blue) is truncated by the elevated noise floor between 8 kHz and 10 kHz.

Another consideration is that the 16-bit soundcard is capable of presenting tone stimuli over a 96 dB dynamic range, so care had to be taken to choose a volume setting which best matched the lower-end of the dynamic range of the device to that of the thresholds of a normal hearing participant. This same constraint applied to the digital-to-analog converter (NI-9629, National Instruments, TX, USA) used in the ABR system.

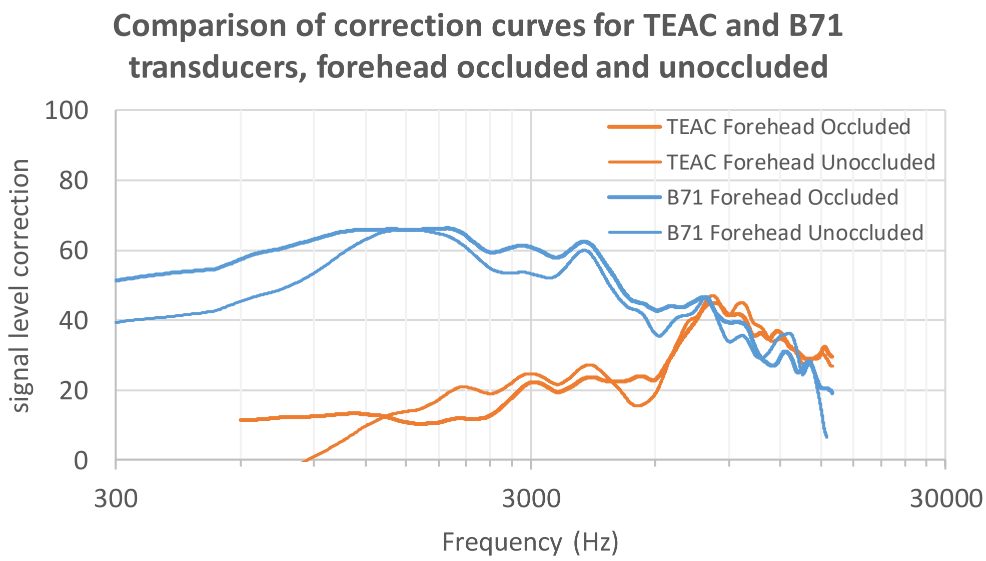
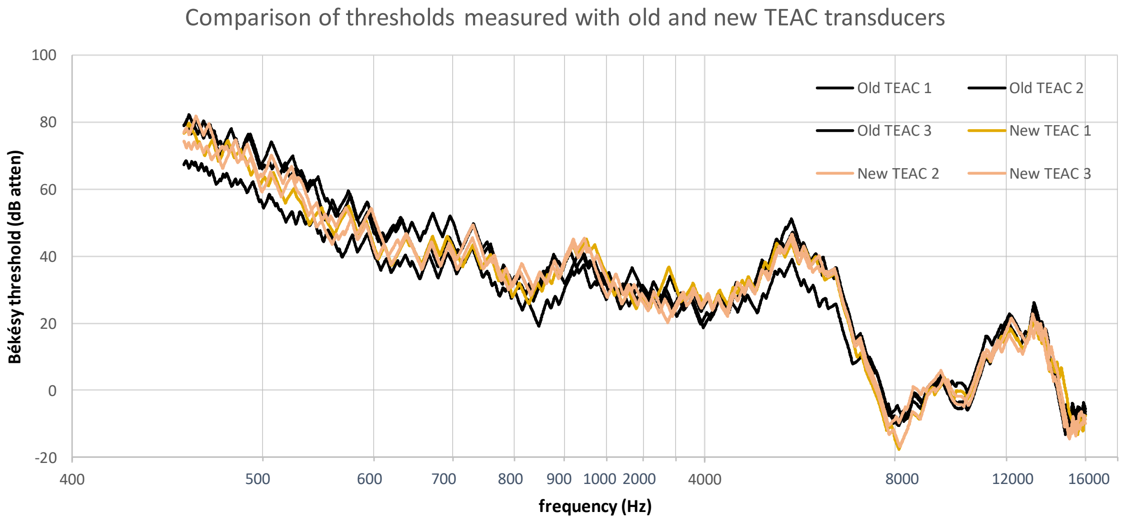


Figure 14: Comparison of the correction factors for the TEAC and B71 bone conductors in the forehead placement in the occluded and unoccluded condition. Note the peak in sensitivity for the B71 below 5 kHz and for the TEAC above 6 kHz. The TEAC transducer was in the mid-volume setting, and the B71 received additional amplification from a NX1 headphone amplifier.

The following plots are the results from the comparison of the TEAC transducers. The top figure is the raw Békésy trace with the bottom figure showing it with 90-point smoothing.



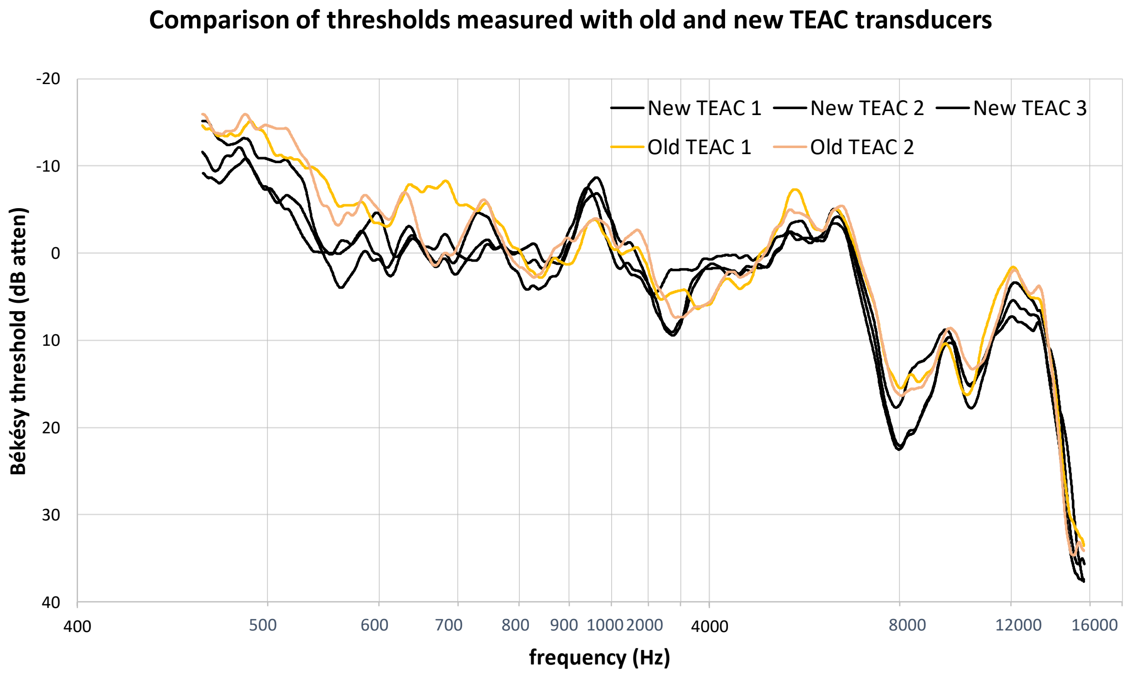


Figure 15: Comparison of the TEAC transducers before and after 90-point smoothing.

The traces as shown in Figure 15 are closely overlaid indicating that the new TEAC is performing in the same manner as the old one. Therefore, with confidence, both transducers can be used interchangeably.

2.3 Discussion

It is important to ensure that the correct hearing thresholds are being measured from the TEAC bone transducer. Babbage (2015) and Popelka et al. (2010) have shown that this transducer can be effective in receiving pure-tone thresholds using the modified Hughson-Westlake method if certain correction factors are used. They used the real ear method in the calibration, as the transducers dimensions and convex shape would not fit on an artificial mastoid; the preferred method of calibration. Though the TEAC and the B-71 transducers used in their studies were calibrated for pure tone audiometry, it is not enough for ABR testing due to the lack of incremental frequency information. It is important for electrophysiology to have the entire frequency curve. It allows us to correct the levels for tone-burst stimuli presented at non-audiological frequencies, and also allows us to correct the frequency response for broadband stimuli such as clicks. For this reason, we used the Békésy real ear method to ensure the full frequency range was being targeted.

It is important to have multiple working transducers that can be used interchangeably. As aforementioned, the TEAC transducer is expensive and hard to acquire. When one became available to purchase, the opportunity was taken. The confidence that both can be used to receive reliable EHF bone conduction thresholds is valuable. This is especially the case for situations when similar studies are running at the same time or when one transducer becomes damaged or misplaced.

3 Chapter 3: Comparison of Amplifiers

Amplifiers play a major role in receiving clean and accurate wave forms. In this section, we compared three different amplifiers to see which would produce the best wave forms and be most beneficial for intraoperative monitoring.

3.1 Methods

3.1.1 Participants

A 28-year-old male audiology student was the only participant that took part in this section of the thesis. The student's primary supervisor was present to help run the ABR and set up the equipment. The participants hearing thresholds are within normal limits in both the standard and EHF range.

3.1.2 Materials

Brainstem responses were sampled at 44.1 kHz using an NI9222 analog-to-digital converter (National Instruments, TX, USA). An HP EliteDesk 800 G1 laptop was used to run custom-written software that delivered the stimuli, along with averaging and processing the responses (Te Pihareinga; O'Beirne, 2015). Ambu Blue Sensor N-00-Sag/AgCI ECG (AMBU Sdn. Bhd., Malaysia) electrodes were used to receive the waveforms from the brainstem. Abrasive tape and conductor gel was also used to prepare the electrode sites. The electrodes were attached to a set of custom-made biological amplifiers (Patuzzi, 2018), that use fibre-optic link between the amplifiers and the demodulator unit. CED1902 amplifiers (Cambridge Electronic Design Ltd, Cambridge UK) and Digitimer D360 amplifiers (Digitimer Ltd, Hertfordshire, UK) were also used for comparison. AC stimuli were presented through a modified Creative Inspire T6160 5.1 surround sound system. The TEAC HP-F100 transducer was used to deliver the BC stimuli. A comfortable recliner chair was also used to ensure maximum relaxation for low EMG.

3.1.3 Procedure

The participant prepared the electrode sited by lightly exfoliating the skin with abrasive tape. The electrodes were then prepared with some conductive gel and placed on the forehead, mastoid and neck. For comparing amplifiers, the electrode montage was doubled, therefore having two electrodes in each placement. The electrodes on the forehead were placed slightly right and left of centre as to not interfere with the TEAC transducer placement. The participant then sat in the chair and the electrodes were attached to the amplifiers. The free field speaker was placed in front approximately 50 cm from his ears. The participant then got as relaxed and comfortable as possible to ensure their EMG was low enough not to interfere with the ABR. 2000 averages of the 100 μs click along with a 14 kHz tone pip were played at five different attenuations through either the free field speaker and/or the TEAC transducer. Recordings from the custom biologic amplifier and the CED1902 amplifier were done simultaneously. Following these recordings, the CED1902 and the D360 amplifiers were used simultaneously for the ABR recordings. The data was collected and formatted in excel. A 50 Hz - 2 kHz filter was used to smooth out the waveforms making them easier to read and compare.

3.2 Results

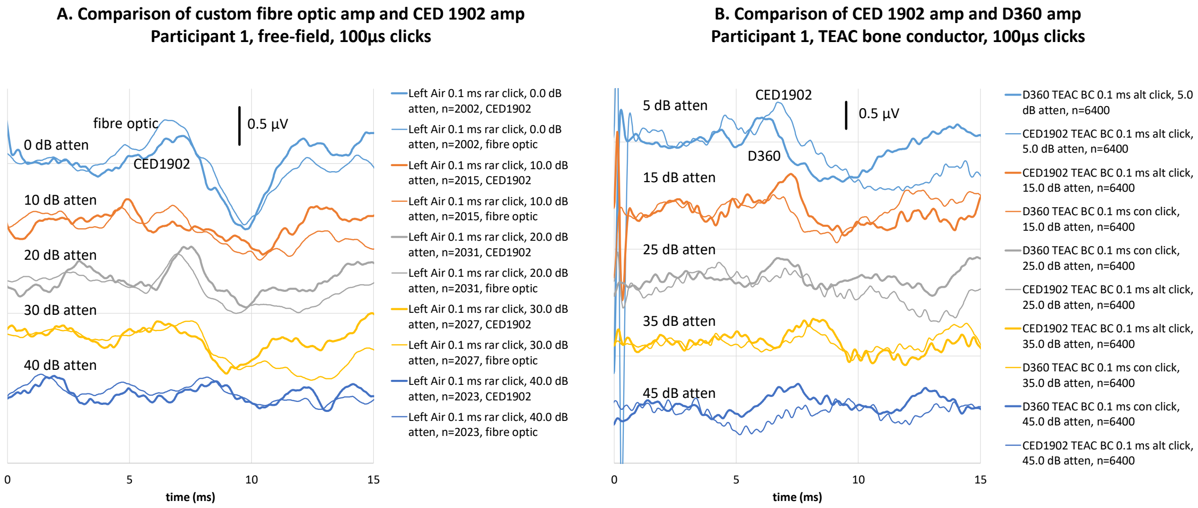


Figure 16: A. Comparison of ABR traces recorded using the custom fibre-optic isolated bio-amplifier and the CED 1902 amplifier. B. Comparison of the CED1902 amplifier and the Digitimer D360 amplifier. In both cases, the pairs of amplifiers were recording from different pairs of electrodes situated adjacent to each other. Filtering: 50 Hz to 2 kHz. DC offset calculated from 3-5 ms window.

As seen in Figure 16 each amplifier produced reliable and clear ABR waveforms.

3.3 Discussion

Amplification is an important part in receiving reliable electrophysiological information. This stage of the study has shown that each amplifier tested could receive robust, clear waveforms. However, the D360 and CED 1902 amplifiers are bigger and need to run off the mains for power, which can cause 50 Hz noise in the traces. For this reason, the custom fibre optic amplifier is best for intraoperative monitoring. It is light weight and can run off battery power which will ensure that no 50 Hz noise is included in the traces. Unfortunately, the charger for the fibre optic amplifier was not available for the rest of this project due to unforeseen circumstances. Luckily, though the fibre optic amp would be best for intraoperative monitoring, all three amplifiers, as shown above, can receive reliable ABR information. For this reason, the D360 amplifier was chosen for the following chapter of this project.

4 Chapter 4: Interleaved AC and BC ABR for ABG Information

This stage of the thesis project was to ensure the mechanism and software created would work in receiving rapid ABG information. This includes interleaving the AC and BC both with click and pure tone stimuli. The way in which we accomplished these goals will be discussed in this section.

4.1 Methods

4.1.1 Participants

The participant for this stage of the study is the same as the one used in Chapter 3.

4.1.2 Materials

Brainstem responses were sampled at 44.1 kHz using an NI9222 analog-to-digital converter (National Instruments, TX, USA). An HP EliteDesk 800 G1 laptop was used to run custom-written software that delivered the stimuli, along with averaging and processing the responses (Te Pihareinga; O'Beirne, 2015). Ambu Blue Sensor N-00-Sag/AgCI ECG (AMBU Sdn. Bhd., Malaysia) electrodes were used to receive the waveforms from the brainstem. Abrasive tape and conductor gel were also used to prepare the electrode sites. The electrodes were then attached to the D360 amplifier (Digitimer Ltd, Hertfordshire, UK). AC stimuli were presented through a modified Creative Inspire T6160 5.1 surround sound system. At this stage of the study, the TEAC HP-F100 transducer was used to deliver the BC stimuli. Class 5 foam ear plugs were used again to simulate a conductive hearing loss. A comfortable recliner chair was also used to ensure maximum relaxation for low EMG.

4.1.3 Procedure

The thresholds of the participant were recorded using the software. AC and BC thresholds were taken from occluded and unoccluded ears with each stimulus being used (100 µs click, 4 kHz and 12 kHz tone bursts). The participant prepared the electrode site by lightly exfoliating the skin with abrasive tape. The electrodes were then prepared with some conductive gel and placed on the forehead, mastoid and neck. The electrodes on the forehead were placed slightly right or left of centre as to not interfere with the TEAC transducer placement. The participant then sat in the chair and the electrodes were attached to the amplifier. The free field speaker was then placed in front approximately 50 cm from their ears. Again, the participants got as comfortable and relaxed as possible to ensure their EMG was sufficiently low. The stimulus was then played through both the free field speaker and the TEAC transducer.

As a test to confirm that the correction factors derived in the previous section were working appropriately in the custom-written evoked potential software, sample click ABR waveforms were obtained using interleaved air conduction and bone conduction stimulation. The derivation of the correction factor for the modified Creative Inspire T6160 5.1 surround sound system is reported elsewhere (Gray, 2014). In addition to the calibration for the combination of transducer and DAC, the software accounted for the acoustic travel time of the free-field stimulus, which depended on the distance between the speaker and the participant.

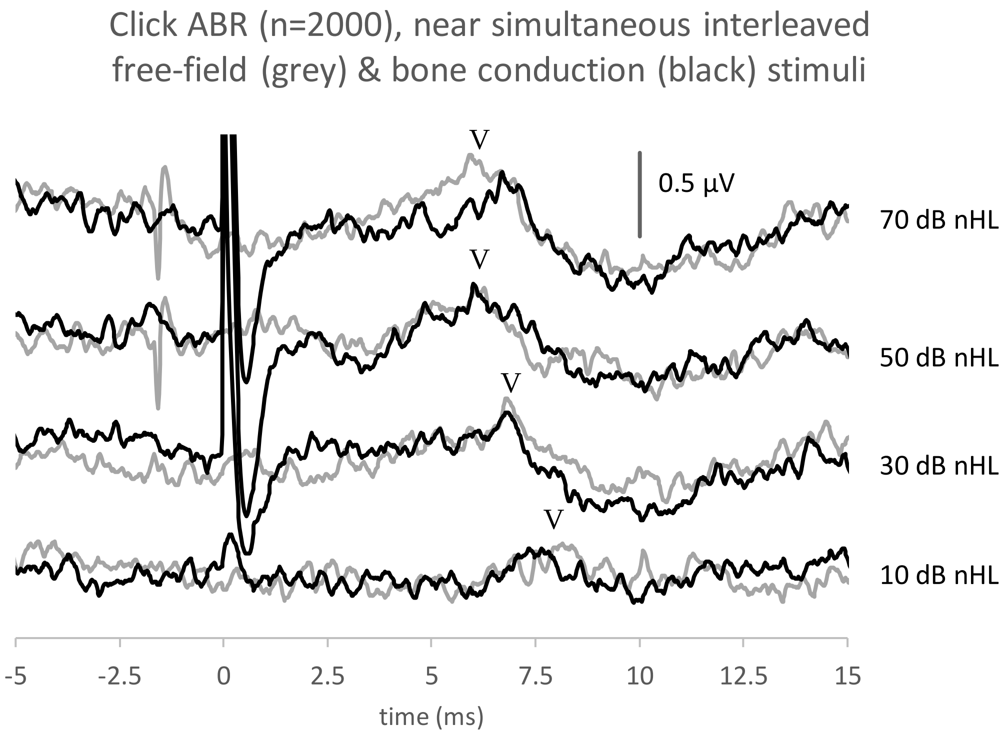


Figure 17: Sample interleaved click ABR waveforms recorded from Participant 1 showing that stimulation at the same level with both calibrated delivery methods produced very similar ABR waveforms. Note the difference in the timing of the stimulus artefact to account for the travel time of the free field speaker situation 50 cm from the participant.

The participant listened to a 100 µs click stimulus and determined their threshold from the custom software and free field speaker with their ears either occluded with ear plugs or unoccluded.

The click was then played interleaving between AC and BC and played at several intensity levels ranging between 0 and 80 dB nHL. ABR was measured with the participants ears unoccluded and then occluded to simulate a conductive hearing loss. In both conditions, the participant received one thousand averages and then took a short break and then received another thousand averages continuing this pattern until approximately four to six thousand averages were measured.

The previous steps were then repeated with pure tone stimuli, with few exceptions. One thousand averages were collected using a 4 kHz and 12 kHz tone burst. At 12 kHz, eight thousand averages total were recorded. The total amount of traces was then split to make replicable waves of four thousand averages for each condition. The same was done with the 4 kHz tone burst, however due to time restraints only four thousand averages were acquired and therefore replicable waves of two thousand averages each were plotted. Furthermore, only three intensity levels were measured at these frequencies, being unable to receive traces at or around.

4.2 Results

The unoccluded AC thresholds for the click stimuli were -5 dB nHL while the occluded thresholds were 25 dB nHL and therefore resulting in a simulated conductive hearing loss of 30 dB nHL. Unoccluded AC thresholds at 4 kHz were 0 dB nHL and 5 dB nHL at 12 kHz. Occluded thresholds were measured at 30 dB nHL for 4 kHz and 35 dB nHL for 12 kHz. The BC thresholds are within 5 dB of the AC unoccluded thresholds signifying no ABG according to the 5 dB test-retest reliability. The simulated conductive hearing loss for the tone burst stimuli was therefore the same as the click, at 30 dB nHL. To express this in sensation level, the thresholds for each condition would be subtracted by the intensity levels found in each figure below. For example, the sensation level for the AC occluded click stimuli at 80 dB nHL would be 55 dB SL.

Clear ABR waveforms are formed through the interleaving of the AC and BC 100 µs click stimuli. Figure 18 shows a clear reliable wave V in the unoccluded condition for both AC (black) and BC (green). Figure 19 also shows clear wave forms for the occluded condition.

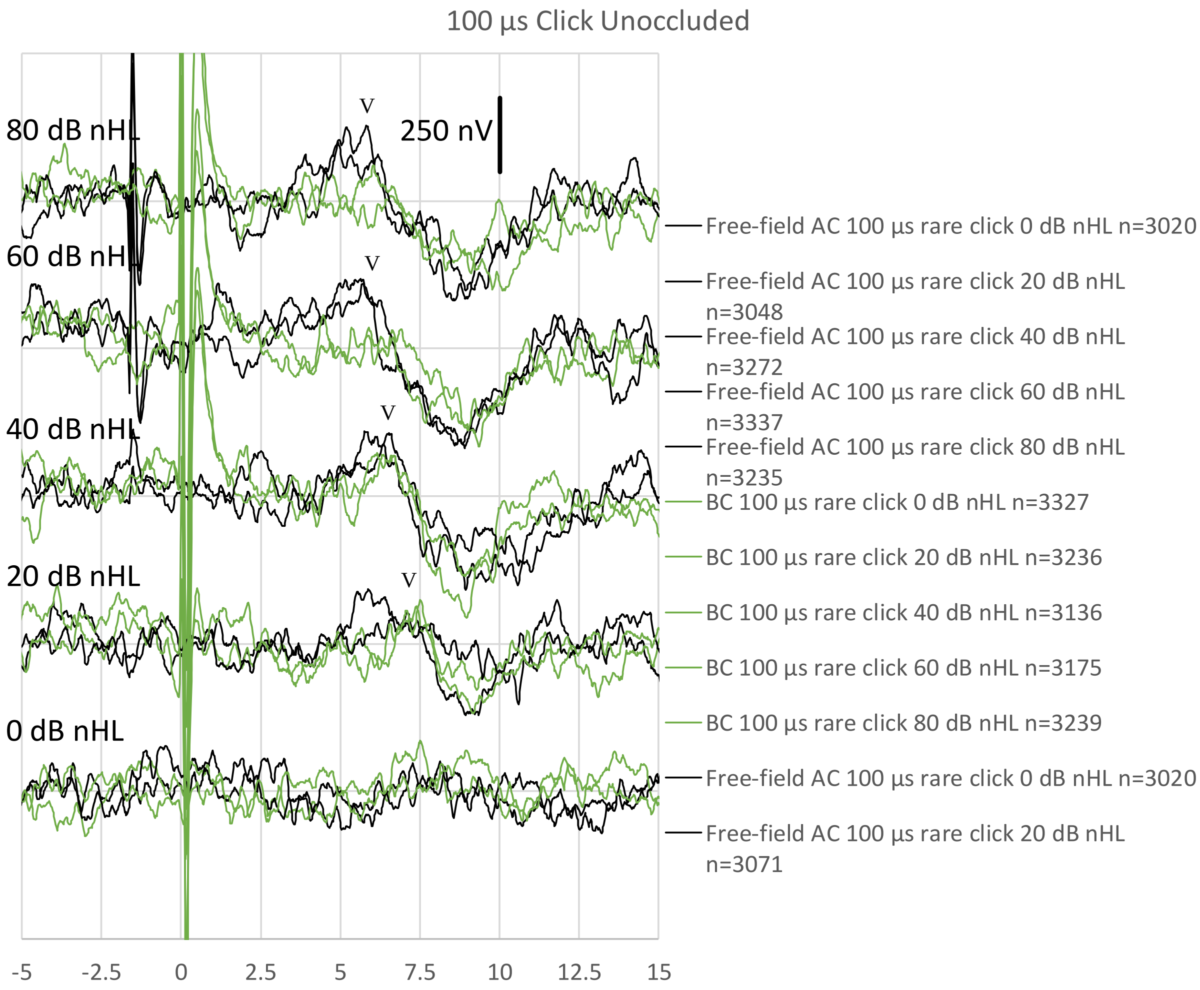


Figure 18: Interleaved AC and BC 100 µs click ABR unoccluded. 80, 60, 40, 20, 0 dB nHL corresponds to 85, 65, 45, 25 and 5 db SL.

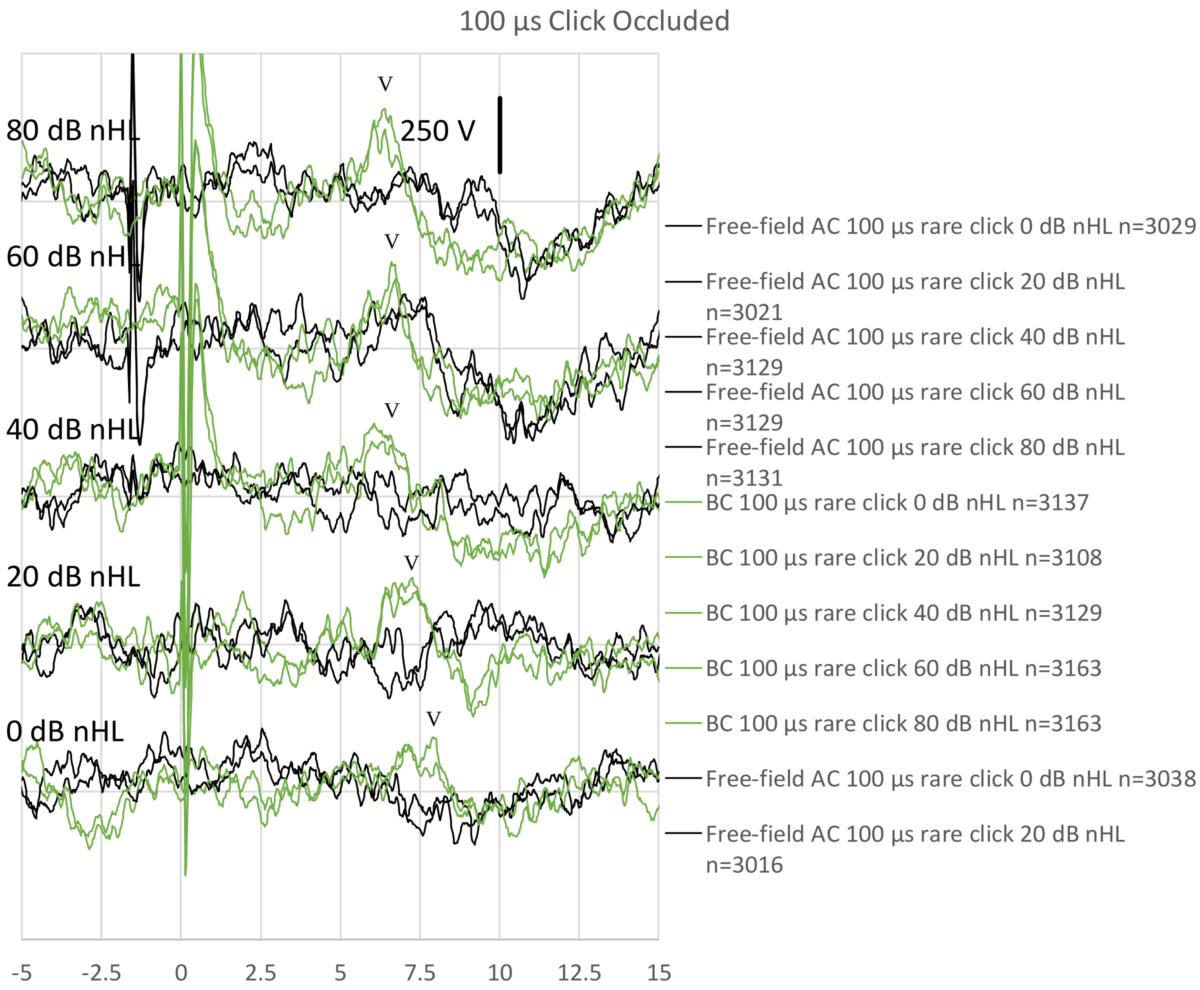


Figure 19: Interleaved AC and BC 100 µs click ABR occluded. With AC occluded thresholds at 25 dB, 80, 60, 40, 20, 0 dB nHL corresponds to 55, 35, 15, -5 and -25 db SL. BC thresholds are the same as the unoccluded AC thresholds and therefore correspond to dB SL in a similar manner.

The latency-intensity function for these wave forms is laid out in the following table. When the participants' ears were occluded to simulate a conductive hearing loss, the difference between the AC and BC latencies were mostly just under 1 msec. with the exception at 40 dB nHL. The BC was shorter and the AC longer which is consistent with conductive hearing losses.

In the condition where the ears were unoccluded, the AC and BC latency differential is much smaller (> .5 msec.), indicating no ABG. The latency of BC is also longer than the AC while the ears were unoccluded. In both conditions, the latencies get longer as the intensity is lowered which is expected with ABR wave V recordings.

Table 3: Latency-intensity function for 100 µs click. Diff = difference. Measurements are in milliseconds (msec).

Level (dB)	Occluded AC (msec)	Occluded BC (msec)	Diff. (msec)	Unoccluded AC (msec)	Unoccluded BC (msec)	Diff. (msec)
80	7.012	6.286	0.726	5.9	6.036	-0.136
60	7.646	6.739	0.907	6.286	6.649	-0.363
40	8.145	7.102	1.043	6.853	7.284	-0.431
20	8.372	7.442	0.933	7.714	7.556	0.158
0				8.236	7.646	0.59

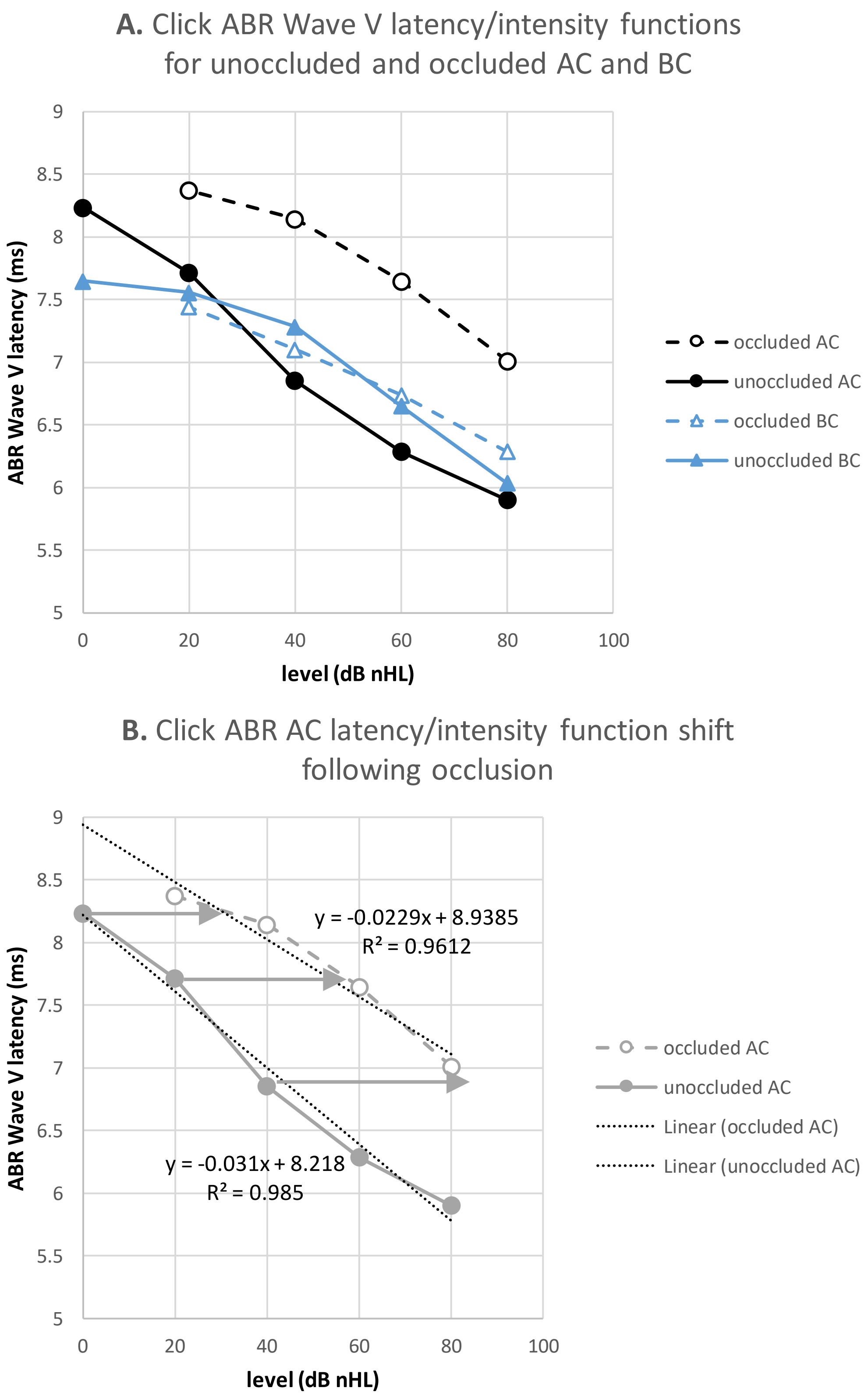


Figure 20: A. Latency intensity functions from data shown in Table 3. B. Linear regression lines for the AC functions give estimates of the conductive loss of around 40 dB.

Following the data collection of the click stimuli to ensure the mechanism was working as desired, 4 kHz and 12 kHz tone bursts were presented to the participant and the data was analysed. Figures 21 and 22 show the unoccluded and occluded wave forms at 4 kHz respectively.

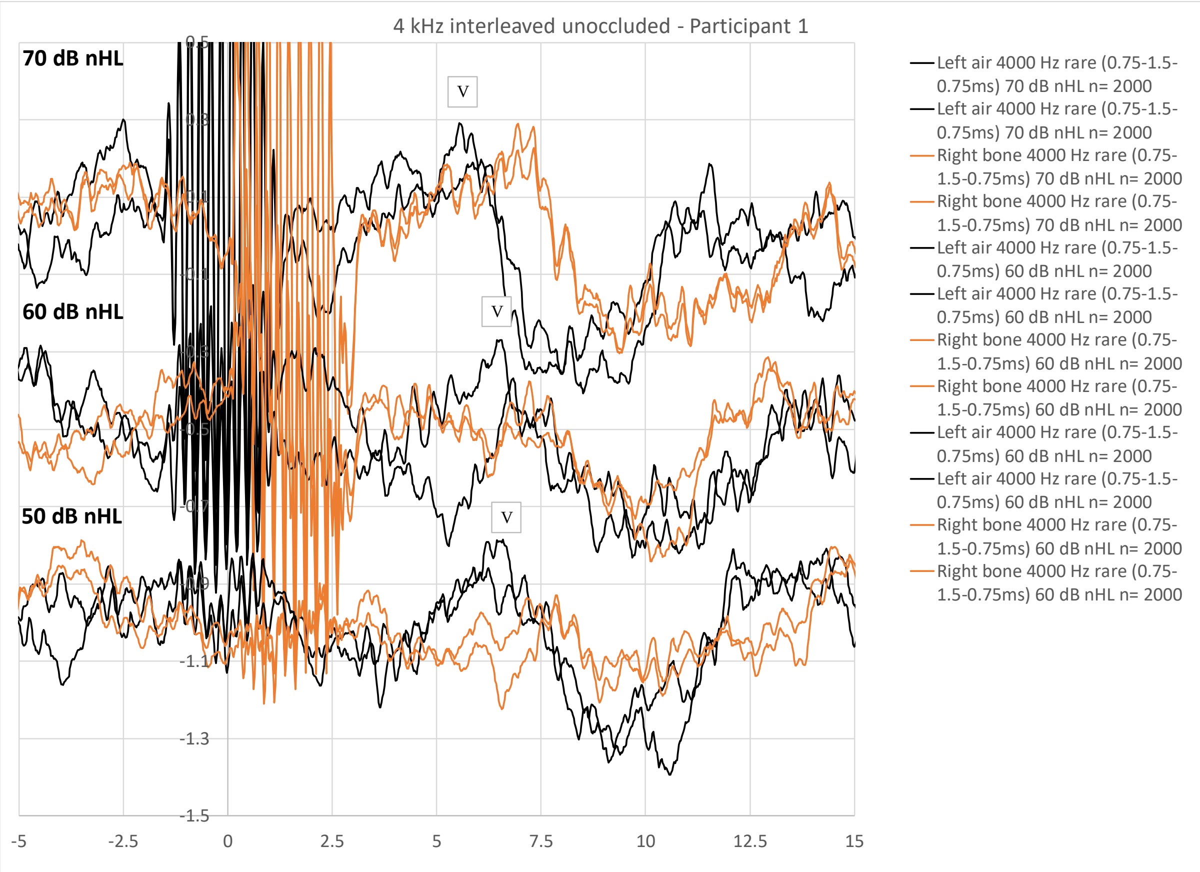


Figure 21: 4 kHz unoccluded interleaved AC and BC ABR at 70, 60 and 50 dB nHL. AC thresholds are 0 dB nHL unoccluded which corresponds to 70, 60, and 50 dB SL. BC thresholds are similar and therefore correspond in the same manner.

Table 4 shows the amplitude and latencies of each condition and the difference between the AC and BC stimuli. The 4 kHz wave forms follow the expected latency-intensity function, with the decrease in intensity, the longer the latency. In the unoccluded condition the AC wave forms are more robust and have a shorter latency than the BC. This is consistent with what we have found with the click and 12 kHz stimuli. The latency separation at 70 dB between the AC and BC in the unoccluded condition is greater than expected. This may be due to the distortion of the pure tone stimuli at 70 dB nHL.

The occluded condition at 4 kHz shows a larger differential shift between AC and BC than that of the unoccluded condition. The amplitude of the BC wave forms is also greater than the AC in the occluded condition in the high and mid intensity levels. This is characteristic of a conductive hearing loss. Even though the traces are noisy, there is a clear difference between the occluded and unoccluded conditions at 4 kHz. This exemplifies that this new mechanism can produce ABR wave forms in the speech range.

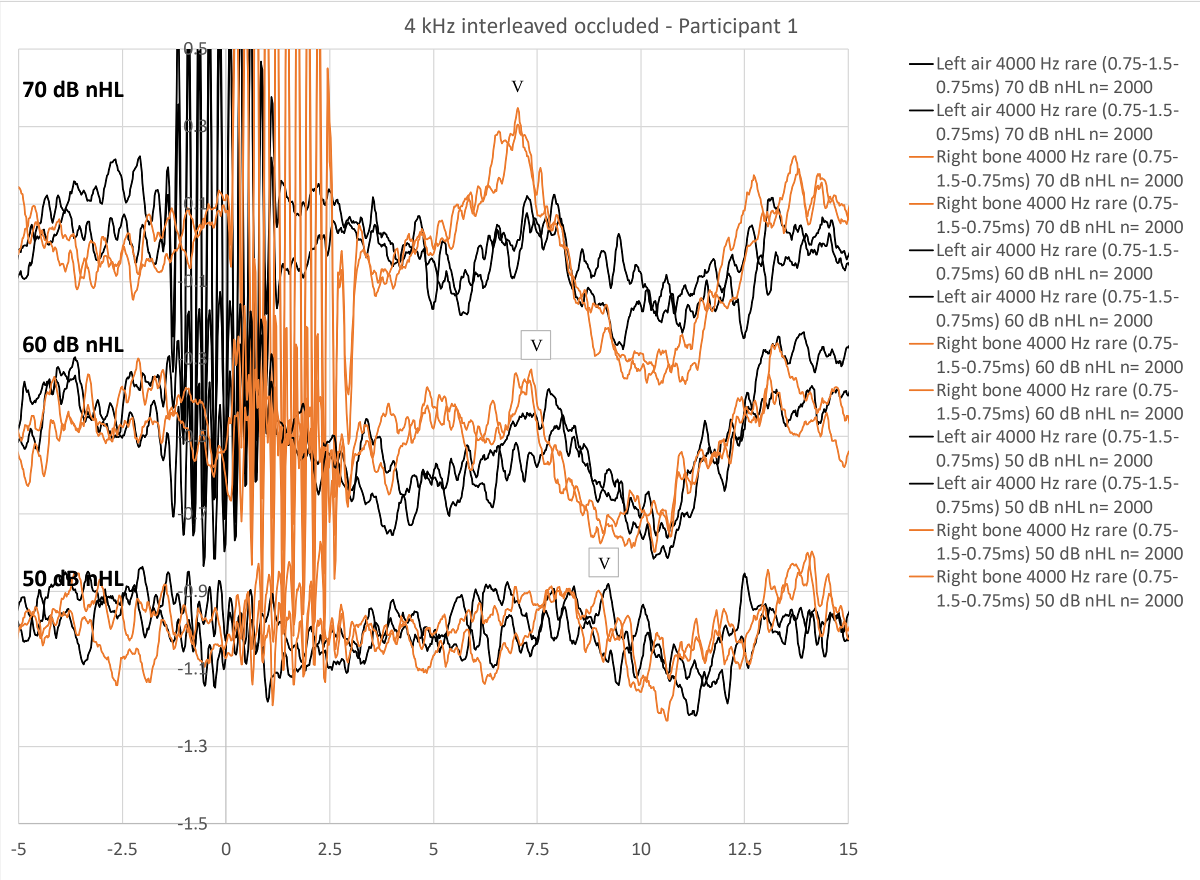


Figure 22: 4 kHz occluded interleaved AC and BC ABR at 70, 60 and 50 dB nHL. AC thresholds are 30 dB nHL occluded which corresponds to 40, 30, and 20 dB SL. BC thresholds are similar to the unoccluded AC thresholds and therefore correspond in the same manner (70, 60, and 50 dB SL).

Table 4: Latency-intensity and amplitude functions for a 4 kHz tone burst ABR. Occl. = occluded, unoccl. = unoccluded and diff = difference.

Estimated Amplitude top-bottom						
Intensity (dB)	AC Occl.	BC Occl.	Diff.	AC Unoccl.	BC Unoccl.	Diff.
70	0.25	0.7	0.45	0.67	0.57	0.1
60	0.4	0.44	0.04	0.55	0.45	0.1
50	0.33	0.33	0	0.57	0.28	0.29
Estimated Latency (msec.)						
Intensity (dB)	AC Occl.	BC Occl.	Diff.	AC Unoccl.	BC Unoccl.	Diff.
70	7.81	7.1	0.8	5.85	7.32	1.47
60	7.82	7.3	0.52	6.53	7.26	0.73
50	9.03	9.2	0.07	6.6	7.85	1.25

The following traces show the input output function at 12 kHz. Due to the difficulty of receiving EHF ABR, and the time restraints, the wave forms are a little noisy. This noise makes it difficult to estimate the true latency-intensity function of wave five. The participants' unoccluded and occluded 12 kHz trace is found in Figures 23 and 24.

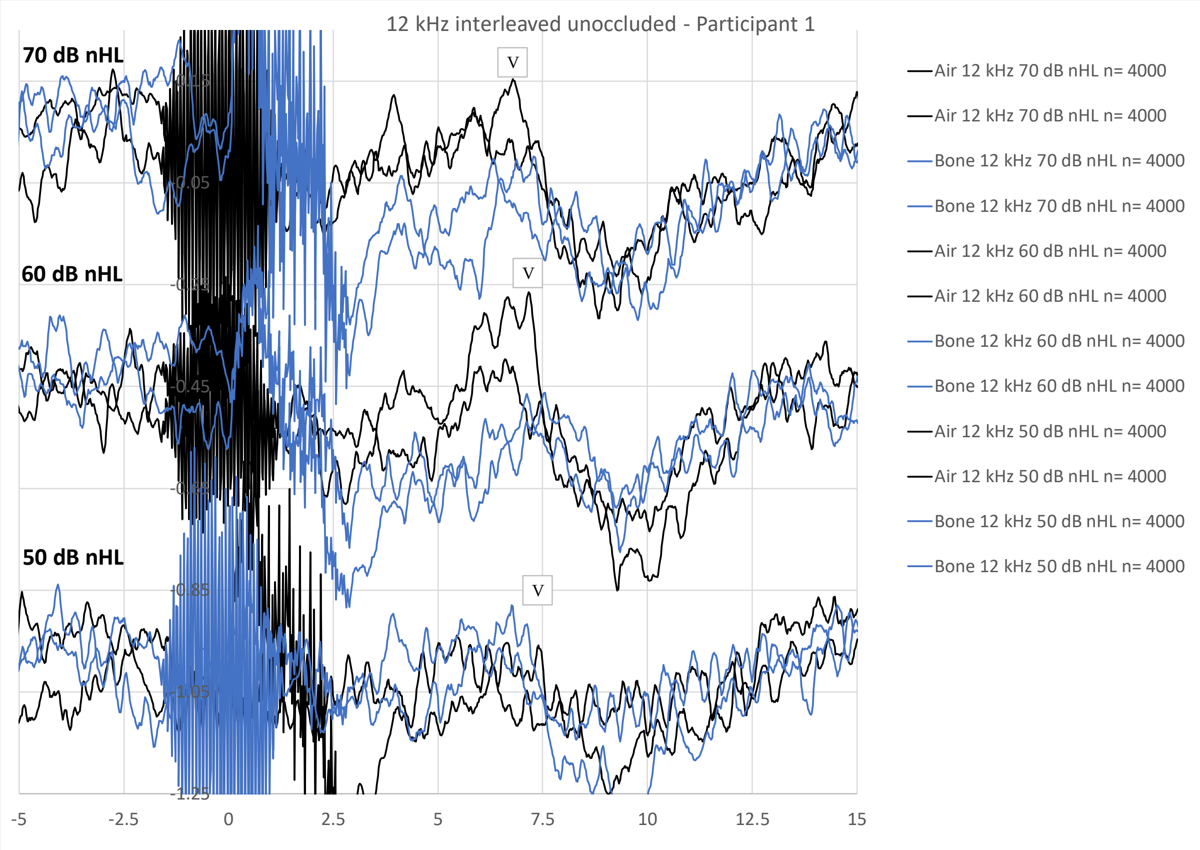


Figure 23: 12 kHz unoccluded interleaved AC and BC ABR at 70, 60 and 50 dB nHL. AC thresholds are 5 dB nHL unoccluded which corresponds to 65, 55, and 50 dB SL. BC thresholds are similar and therefore correspond in the same manner.

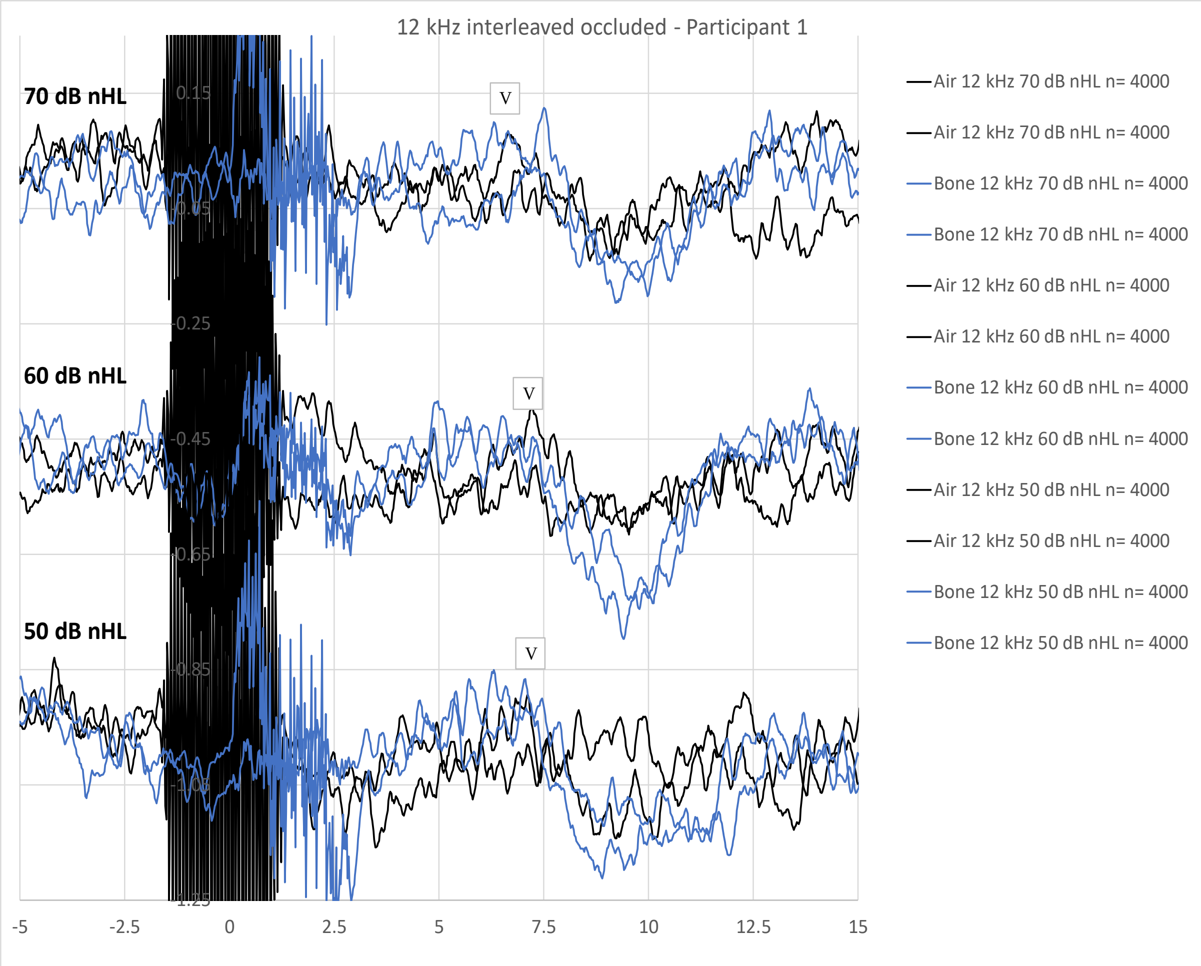


Figure 24: 12 kHz occluded interleaved AC and BC ABR at 70, 60 and 50 dB nHL. AC thresholds are 35 dB nHL occluded which corresponds to 35, 25, and 15 dB SL. BC thresholds are similar to the unoccluded AC thresholds and therefore correspond in the same manner (65, 55, and 45 dB SL).

Though the waveforms are noisy, wave V can still be seen clearly at all intensity levels tested. Estimation of the latency showed that in the unoccluded condition, BC latencies were longer than those of the AC with exception at 50 dB nHL. This is like that found with the click stimuli. In the occluded condition, the latencies of the AC and BC are close at the highest and lowest intensity tested. However, there is a greater shift at 60 dB nHL with a difference of 0.72 msec. Like the click stimuli, the 12 kHz tone bursts latency gets longer as the intensity decrease for the 70 and 60 dB nHL. The differential is much smaller and harder to determine with these traces.

The estimation of amplitude was also examined to see if there were any differences. By looking at the wave forms and measuring from peak to valley, there is a clear amplitude differences in the occluded condition, with the BC being more robust. In the unoccluded condition however, the opposite is true. The AC wave V is larger except for the lowest intensity of 50 dB nHL. This amplitude change is characteristic of a conductive hearing loss, as the AC wave form is smaller than that of the BC.

Table 5: Latency-intensity and amplitude functions for a 12 kHz tone burst ABR.

Estimated Amplitude top-bottom						
Intensity (dB)	AC Occl.	BC Occl.	Diff.	AC Unoccl.	BC Unoccl.	Diff.
70	0.23	0.33	0.1	0.45	0.32	0.13
60	0.21	0.4	0.19	0.57	0.3	0.27
50	0.23	0.35	0.12	0.3	0.43	0.13
Estimated Latency (msec)						
Intensity (dB)	AC Occl.	BC Occl.	Diff.	AC Unoccl.	BC Unoccl.	Diff.
70	6.7	6.35	0.35	6.8	7.2	0.4
60	7.3	6.58	0.72	7.2	7.5	0.3
50	7.2	7	0.2	7.2	6.7	0.5

4.3 Discussion

The focus of this stage of the project was to ensure that the TEAC transducer along with the software and freefield speacker could eilicit an ABR from a single participant in both the standard and EHF range. ABR is a reliable way to receive objective thresholds in the standard frequencies via AC and BC. It has also been shown in other studies that AC ABR can be achieved using EHF tone bursts (Fausti et al., 1993; Fausti et al., 1993). Furthermore, ABR has been used as a way to monitor hearing thresholds on human subjects during middle ear surgery but only using 1 kHz tone pip and click stimuli (Hsu, 2011; Ren et al., 2017; Sturgill et al., 2008). EHF ABR in both AC and BC for intraoperative monotoring however, is also desirable in human subjects. By monitoring this frequency range, one can see if there is damage being done iatrogenically. By using both AC and BC to monitor these frequencies, the type of hearing loss can be determined and to see if the ABG is closing as a result of the surgery.

As aformentioned, Bergin et al. (2015) showed that the TEAC transducer can produce reliable ABR waveforms in guinea pigs across a wide range of frequencies. They also mentioned in their study that the headphone amplifier was removed. By doing this, it may have reduced the problems with noise floor and output that could be achieved by this trancducer. This could be a recommendation for future reasearch.

This stage of the project has examplified that both AC and BC ABR can be achieved in the standard and EHF range using our newly designed method. In the most part, the waves follow the same latency-intensity function found in the study done by Fausti et al. (1993) however, they were not as clear. The differential was not as long between AC and BC in the 12 kHz occluded condition as they were in the click evoked occluded condition. These unexpected findings can be due to a calibration error and the noise on the wave forms and should be studied in more depth in following studies.

Although the latencies had very little change in the occluded condition, the amplitude differences between the AC and BC was noticable, the BC being in the most part larger which is typical for conductive hearing losses. The eroneous results in the 4 kHz unoccluded condition at 70 dB may be due to the distortion of the stimuli at the incresed intesity level. If there was distortion, this stimuli would act more like a click rather than a pure tone cause more neural firing and a quicker and and more robust wave form.

Interleaving the AC and BC stimuli helped in receiving rapid ABG information. The real time saver however is when different frequncies are interleaved together. Due to time restraints and the focus of this thesis, this was not accomplished and is in need of future research. The main purpose of this portion of the study was to test and receive wave V from the ABR mechanism developed. It has been shown that wave V can be elicited via AC and BC tone bursts in the standard (4 kHz) and EHF (12 kHz) range.

5 Chapter 5: Conclusion

5.1 Clinical Implications

The focus of this project was to create a method that could estimate the ABG in both the conventional as well as in the extended frequency range. It was also to ensure that the ABR wave forms could be produced rapidly and reliably by interleaving the AC and BC stimulus. There are many clinical implications from this project, and a few will be discussed in detail in this section.

5.2 Middle Ear Surgery

The method created in this thesis was designed for the operating theatre. It ensures that the surgeon can perform a procedure with little to no interference. This was done by using a free field speaker and placing the bone transducer on the forehead, keeping the operating field open and clear. The method was also designed to help the surgeon determine if the procedure has been successful. Measuring the ABG while still in the operating room will help the surgeon determine if further work needs to be performed. This would therefore reduce the need for revision surgery, increasing the satisfaction of the patient as well as reducing surgical costs.

As discussed previously, there is a risk that middle ear surgery can cause temporary and permanent threshold shifts due to noise caused by surgical equipment and procedures performed by the surgeon (Hilmi, McKee, Abel, Spielmann, & Hussain, 2012; Kylen, Kylé, n, & Arlinger, 1976; Murugasu, Puria, & Roberson Jr, 2005; Puria, Kunda, Roberson Jr, & Perkins, 2005; Spencer & Reid, 1985; Strömberg et al., 2010). This damage is first seen in the EHF range, making it important for clinicians to monitor that range during surgery. The TEAC bone transducer has been shown as a reliable device for EHF bone conduction. By measuring the ABG in the EHF range, the site of lesion can also be determined, that being sensorineural or conductive. With this information, the surgical procedure could be modified to decrease the chance of damage in the EHFs and therefore future hearing impairment in the speech range.

5.3 Special Populations

Receiving hearing thresholds from infants and other populations that cannot perform a standard hearing examination can be difficult and time consuming with the present ABR system. This is especially true with infants as the ABR is preferably done while the baby is sleeping. In many cases the baby wakes up before the full results are complete and therefore needing a return appointment. This new ABR method may be used to receive quicker results through the interleaving of the AC and BC. Although the sleep of an infant is unpredictable, the faster reception of the ABG and hearing thresholds could reduce the need for further appointments.

The faster a hearing impairment is discovered the quicker a remedy can be implemented, such as hearing aids or the insertion of ventilation tubes/grommets. This again, is especially important for infants and their speech and language acquisition. Generally, the less time to receive objective hearing thresholds, the better it is for both the client and clinician, making this project an important first step to receiving more rapid objective hearing information.

5.4 Limitations

This thesis project is extremely technical and complex. Due to the inexperience of the student along with the time restraints, there are many limitations to this study that will be discussed in this portion of the thesis. It is important to note that there could be many other technical limitations that are not mentioned in this section due to the lack of knowledge and inexperience of the author.

The sample size for the calibration of the bone conductor was small with many of the participants not completing each condition. The attempt was to receive a flat frequency response from the TEAC transducer that would show the participants thresholds in dB HL. This was accomplished however, the sample size for this project was too small and therefore not robust enough to be true representation of dB HL. Consequently, this data will not be suitable for clinical application until a larger sample size is used. The same is true for the testing of the full interleaving ABR method. With only one participant, generalisations for the whole population cannot be made.

Simulating a conductive hearing loss with ear plugs is also a limitation. This does not consider the different conductive pathologies and the effects they may have on the ABR. Furthermore, due to time restraints, separate ear information was not recorded using masking. Therefore, the appropriate masking level was not determined and should be kept in mind for future projects.

ABR is a small and somewhat difficult electrophysiological technique to receive large clean waveforms. It was therefore difficult to get reliable latency-intensity functions from the wave forms we received. Other electrophysiological techniques that give more robust wave forms such as the PAMR and transtympanic electrocochleography may be more suitable for receiving this information.

The testing was in an idealised setting with very little noise, both electrical and ambient. This would not be the case in an operating theatre and so the performance of this method in that setting cannot yet be determined.

The main goal however was to create mechanism for rapid ABR and ABG information and then see if it would work. I believe that this goal has been accomplished even though there are many things to work out in future projects.

5.5 Future Research

There are many great possibilities for future research that can improve upon this project.

The limitations of a small sample size can be rectified with a project dedicated to finding and testing both normal hearing individuals and those with a conductive hearing loss. This would ensure that the new method works across a wider population and with different middle ear pathologies. A greater focus could also be put on the interleaving of the stimuli to see how much faster results can be obtained. Furthermore, the TEAC could be modified like that done by Bergin et al. (2015) by removing the headphone amplifier to see if this would help reduce the noise floor and increase the output at the higher frequencies. After this is accomplished, the new method can be taken into the operating theatre to see how it performs on those receiving middle ear surgeries.

Another avenue of research could involve receiving objective hearing thresholds for infants and other special populations. As aforementioned, the interleaving of the AC and BC can decrease the time in receiving hearing thresholds. This in turn would reduce the risk of having the client return for another appointment to finish the testing. Comparing this new interleaved AC and BC method with the present ABR program would show if the current program can be improved upon.

5.6 Summary and Conclusion

The aim of this study was to create a rapid and reliable method of test hearing thresholds during middle ear surgery. The focus was on estimating the ABG caused by middle ear pathologies at the EHF range. These goals were accomplished in this thesis by calibrating the TEAC bone transducer so that it could be used to receive reliable BC thresholds at the EHFs. To receive reliable wave forms and determine which would be best for intraoperative monitoring, we compared different amplifiers. The custom fibre optic amplifier was found to be reliable in creating clear waveforms. Furthermore, it is light weight and battery power making it ideal for the operating room environment. Finally, we tested the method with a 100 μs click and frequency specific stimuli. The interleaving AC and BC ABR method is functional in receiving ABR wave V in both a normal hearing subject and a simulated conductive hearing loss with both the click and 4 kHz and 12 kHz tone burst stimuli. We conclude that this new ABR method has the potential to receive objective hearing thresholds intraoperatively in both the standard and extended high frequency range.

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