Finding the Optimal Head Position for Bone Conduction Sound Measurements when Using a Skin Microphone

Master's thesis in Biomedical Engineering

Emil Blomster
Emil Lukić

DEPARTMENT OF ELECTRICAL ENGINEERINGG
CHALMERS UNIVERSITY OF TECHNOLOGY
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Department of Electrical Engineering
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Unit of Biomedical Signals and Systems
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Supervisor: Sabine Reinfeldt, Department of Electrical Engineering
Supervisor: Karl-Johan Fredén Jansson, Department of Electrical Engineering
Examiner: Sabine Reinfeldt, Department of Electrical Engineering

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Department of Electrical Engineering
Division of Signal Processing and Biomedical Engineering
Unit of Biomedical Signals and Systems
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: The skin microphone from Sonion used in this study

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Chalmers University of Technology

Abstract

The global problem of hearing loss, which affects roughly 1.5 billion people, has been addressed for hundreds of years. In the 1970s, the concept of bone anchored hearing aid was developed, transmitting vibrations directly to the skull bone and is estimated to be implanted in over 300 000 patients worldwide, mainly who are suffering from conductive or mixed hearing loss. Now there are several models of implantable bone conduction hearing aids on the market, and there is a need to examine their sound quality in place. The aim of this study was to determine the optimal position when using a skin microphone to measure bone conducted sound induced in the skull bone. The optimal position could then be used in a subjective assessment of the sound quality when listening to a person's bone conducted sound. The same position could possibly be used in a verification method when fitting bone conduction devices, similar to real ear measurements for air conduction hearing aids.

In the physical measurements, a skin microphone based on an electric condenser microphone from Sonion was used to measure bone conducted sound. In the tests, two different transducers were used as sources of the bone conducted sound; the audiometric transducer Radioear B81 and an Intenso hearing aid on softband. Tones at specific frequencies and levels were applied from a clinical AC40 audiometer from either a speaker as sound field exposure to the Intenso sound processor or directly to the skull from the B81. The measurements were divided into three different trials. In the first trial positions on the forehead and around the ear were examined, as well as the effect of hair between the microphone and the skin. In the second trial, higher frequencies and additional positions on the head were tested. In the final trial, the most promising positions were chosen and tested on four test subjects. A test-retest was performed on one of these four subjects.

The results showed that the hair had an negligible effect on the skin microphone for these test subjects and that the ipsilateral eyebrow was the most stable position between subjects for both devices when comparing the left and right sides. Each subject had different optimal positions, primarily positions on the ipsilateral side of the head. Another criterion investigated the positions with the lowest standard deviation between measurements for all subjects, where the ipsilateral eyebrow for the B81 and the ipsilateral positions on the head for the Intenso had the lowest value. Future research could examine how much the sound leakage and pressure of the skin microphone affect the measurements.

Keywords: Bone Conduction, Bone Conduction Device, Air Conduction, Hearing Aid, Bone Anchored Hearing Aid, Sound, and Decibel.

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Emil Blomster & Emil Lukić, Gothenburg, June 2023

List of Acronyms

Acronyms in alphabetical order:

AC	Air Conduction
BAHA	Bone-Anchored Hearing Aid
BC	Bone Conduction
BCD	Bone Conduction Device
BCDs	Bone Conduction Devices
BCI	Bone Conduction Implant
BEST	Balanced Electromagnetic Separation Transducer
CAD	Computer-Aided Design
dB	Decibel
EEG	Electroencephalography
NF	Noise Floor
HL	Hearing Level
REM	Real Ear Measurement
RM	Reference Microphone
SD	Standard deviation
SM	Skin Microphone
SPL	Sound Pressure Level
SSD	Single-Sided Deafness
THD	Total Harmonic Distortion
TM	Tympanic Membrane

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1

Introduction

Hearing loss is a global problem, with roughly 1.5 billion people suffering from some kind of hearing disorder [1]. Leading to social exclusion, fewer children going to school, and costs society approximately 980 billion dollars yearly [1]. The first hearing aid dates back to the 1200s, utilizing animal horns, the first breakthrough was in the 1700s, using the classical ear trumpet [2]. In the early 1900s, the first electronic hearing aid was developed to amplify sound with electronics [2]. In the 1970s, a new concept of hearing aid was developed, bone-anchored hearing aid (BAHA), which helped people with conductive hearing loss, mixed and single-sided deafness (SSD) [3]. The difference with BAHA compared to an ordinary hearing aid is that it converts airborne sound to vibrations and sends it directly to the cochlea via the skull bone, utilizing the bones' ability to transfer sound as bone conduction (BC) which in 2022 was used by approximately 300 000 people [3], [4].

By converting sound waves travelling through the air to electrical signals, the sense of hearing can be perceived [5]. For an individual not suffering from hearing loss, the sound waves are funnelled down the auditory canal to the ear drum, which starts to vibrate [5]. These vibrations propagate through the auditory chain until it reaches the inner ear and the cochlea, where the vibrations cause hair cells to move, creating electrical signals that can be sent to the brain [5]. People with conductive hearing loss have a dysfunction in the middle or outer ear, leading to the sound wave not reaching the cochlea, which bone conduction devices (BCDs) help with by conducting sound directly to the cochlea avoiding the outer and middle ear [6], [7].

The market for BCDs has expanded from the first BAHA device in the 1970s to a thriving and competitive market today, with different types of devices and techniques using BC [7]. Two different techniques, direct-drive and skin-drive, are available today, and several BCDs are available in both categories [3], [7]. The transducer in direct-drive devices is connected directly to the skull bone with no skin in-between the vibrations [7]. Two different kinds of direct-drive techniques are available, the first one penetrates the skin with a screw attaching to the skull bone, and examples of this type of technique from companies are Baha from Cochlear Bone Anchored Solutions AB (Mölnlycke, Sweden) and Ponto from Oticon Medical AB (Askim, Sweden) [7]–[9]. The other direct-drive technique in use today implants the transducer under the skin, and no skin penetration is needed [7]. Bone conduction implant (BCI), mentioned in [3] and [10], and the Bonebridge from MED-EL (Innsbruck, Austria) are examples of devices implanted under the skin [7]. Skin-drive devices do not penetrate the skin and send vibrations through the skin to the skull bone, and the device can be attached with three different methods [7], [11]. The first method uses a softband, such as Oticom Medical's Ponto or the Cochlear Baha Start [7], [11]–[13]. The second technique uses an implanted magnet and a magnet over the skin to attach itself, and the Baha Attract (Cochlear Bone Anchored Solutions AB), and the Sophono (Medtronic) system are examples of devices that use this method. [7], [14]. The last attachment method uses an adhesive material called Adhear (MED-EL, Austria)[11], [15].

In order to know if a patient with hearing loss is given the correct amplification from a hearing aid, real ear measurements (REMs) are commonly performed on air conduction (AC) hearing aids [16]. REM tests how well an AC hearing aid amplifies the sound for a patient, and this is essential because calibration might be needed [16], [17]. However, for BCDs, there is no similar test method available to use in clinical settings [16]. BCDs can be operated into the skull bone, and before closing the surgery, it is essential to test the hearing aid's performance to avoid additional follow ups [11], [18]. Research has been done to find a similar method as the REM for BC, for example, using the nasal cavity to measure sound pressure with a sensor in the nostrils [16], [18]. The BCDs vibrations can be measured as sound pressure instead of measuring the vibrations directly [18]. This method could possibly confirm that the BCD works before the operation procedure ends [18]. Researchers at Chalmers University of Technology in Sweden and the University of Alberta in Canada have developed a unique method using a skin microphone (SM) that measures the BC sound radiated from the skull bone [16], [19]. One study showed promising results using the SM on the forehead, and analysing the data can indicate how much the BCD amplifies the patient's sound compared to without the hearing aid [16]. Nonetheless, a protocol and an examination that tests if the BCDs give the desired amplification, needs to be developed further to improve the verification of such devices in clinical settings. Finding the optimal position for the SM on the head would be one step further in developing such a verification method.

1.1 Aim

This project aims to determine where to position a SM to most accurately measure the BC sound induced in the skull bone from a BCD. Different signals will be sent via a BCD, and the sound from the device will be examined. The idea is that different signals and positions of the SM will lead to an optimal signal to examine if the SM converts the sound properly or not. The following questions will be answered:

1. Where is the optimal position of the SM?
2. What type of signal should be sent via the BCD?
3. Is the optimal position of the SM and test signal different between test subjects?

1.2 Scope

The project focuses on the SM position on the head and which type of signal to use. In the list below are the limitations:

- The test will be performed with different kinds of skin-drive techniques.
- The amount of people being tested will be limited.
- Only positions on the skull will be investigated.
- The subjects being tested will not have any type of severe hearing loss.
- Only signals that are comfortable for the subjects will be analysed.

1.3 Figures

The figures in the report have either been made by the authors or Louise Bohl. When Louise Bohl made the figures, her name is in the caption of the figures, otherwise, the figure is made by the authors. The authors have permission from Louise Bohl to use her drawings. No figure was taken directly from another report. However, figures with other reports data values were taken, and credit is given in the caption.

2

Theory

This chapter will present information used in the method, result and discussion. Information about the ear's anatomy and then the function of the hearing mechanics and hearing loss will be introduced. Also, sound, hearing aids, sensors used, statistical methods, and the method known as 10-20 methods to measure positions on the head will be explained in detail.

2.1 Anatomy of the Ear

The organ responsible for perceiving sound is the ear, according to Tortora and Derrickson [5], which this section is based on. The ear is divided into three parts; the outer, middle, and inner ear, and their different functions will be explained. Figure 2.1 and 2.2 display the ears' different anatomical parts.

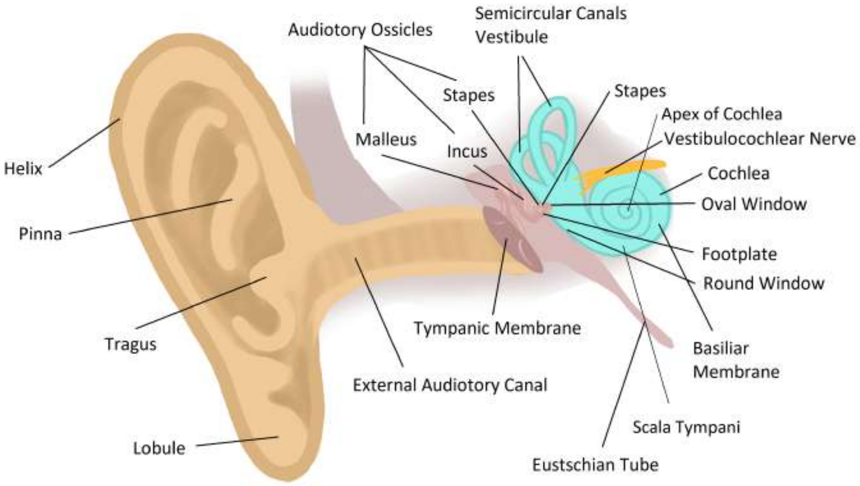

Figure 2.1: The anatomical parts of the ear are shown in the figure. The orange/brown part is the outer ear, the light purple is the middle ear, and the blue is the inner ear. These parts are essential to understand hearing mechanics. The figure is drawn by Louise Bohl, and the authors have permission to use it.

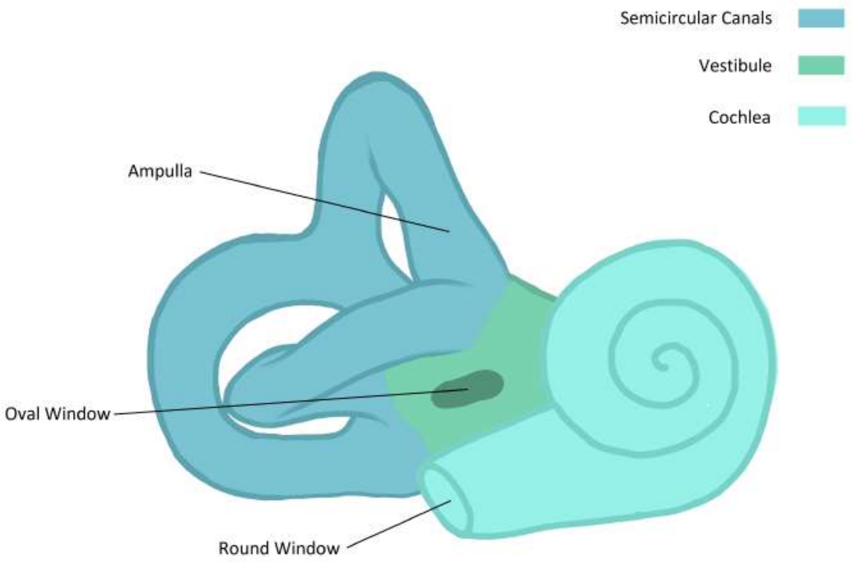

Figure 2.2: The figure shows a close-up of the inner ear. The three different areas of the inner ear are displayed with different colours. The ampulla, round window and oval window are portrayed in the figure. The figure is drawn by Louise Bohl, and the authors have permission to use it.

The outer ear is the outermost part of the ear, starting with the pinna seen in Figure 2.1. It consists of cartilage and an outer layer of skin. The shape of the pinna is for collecting sound and channelling it to the eardrum, also known as the tympanic membrane (TM), which is the intersection that separates the outer and middle ear. The TM has a cone-like shape and covers the opening of the middle ear cavity.

The middle ear consists mainly of an air-filled space connected to the back of the nose by the Eustachian tube and the auditory ossicles. The Eustachian tube consists of flexible cartilage and bone. The Eustachian tube help to equalize the air pressure between the nose and the middle ear. The middle ear helps with hearing by using the auditory ossicles, the malleus, incus and stapes, to conduct sound from the TM to the inner ear. The malleus is the first bone connected to the TM and then runs up to a cavity above it. Here, it articulates with the incus, which is connected to the stapes. The footplate, a part of the stapes, covers the oval window where the middle ear meets the inner ear.

The inner ear, also known as the labyrinth, is where vibrations are converted into nerve signals and sent to the brain for sound interpretation. It is surrounded by the bony cochlea and filled with fluids known as the perilymph and endolymph. Within this volume lies hair cells with the functionality to transduce the vibrations from the stapes into nervous impulses that can be picked up and sent to the brain by nerve fibres. This is because the cochlea is filled with fluids, there needs to be another opening where the fluid space can expand and be compressed as the foot plate vibrates. As the foot plate vibrates it causes pressure waves that propagates to the other opening of the cochlea, the round window. Another essential part of the inner ear is the basilar membrane. It separates the scala media and scala tympani from each other, and it can be seen as the base for the hair cells. Its physical properties vary, making it resonant at different parts for different frequencies throughout the cochlea. For example, the hair vibrates for lower frequencies close to the apex.

2.1.1 Anatomy Directional Terms

Anterior means the frontal part of the head, and posterior is the back of the head, opposite side of the head compared to anterior [5]. Medial is close to the middle, and anterior, posterior and medial are visualised in Figure 2.3 [5]. Ipsilateral implies the same side as a separate object, and contralateral is the opposite side of an object, this is displayed in Figure 2.4 [5].

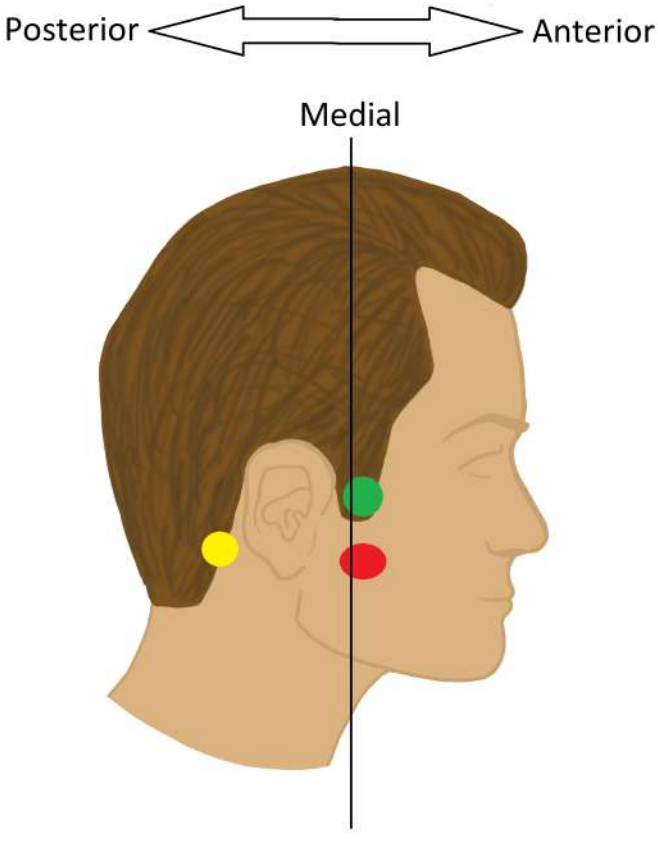

Figure 2.3: An arrow showing the anterior and posterior direction, and the yellow circle is the placement of the B81 or the Intenso. Green and red are two positions measured on. The black line in the middle of the head shows the medial position. The figure is drawn by Louise Bohl, and the authors have permission to use it.

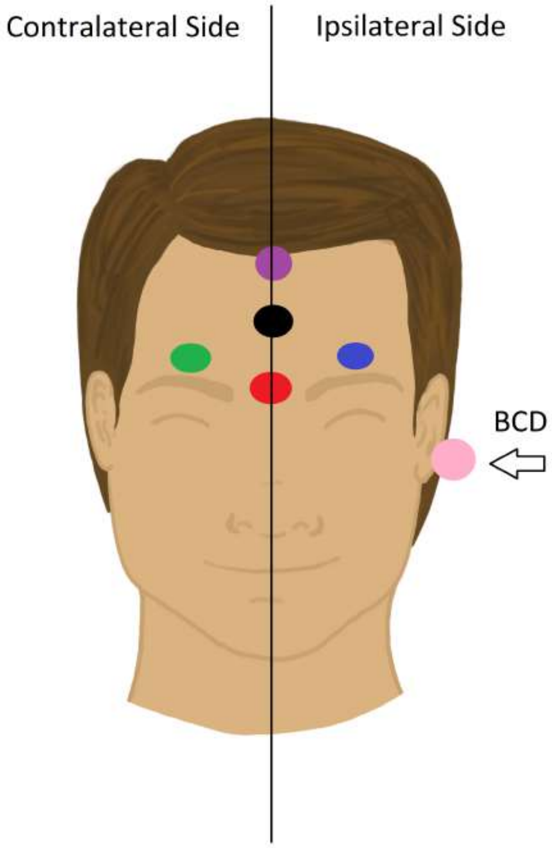

Figure 2.4: The figure shows the ipsilateral and contralateral sides to the BCD. The BCD position is the pink circle, and the position on that side divided by the black line is on the ipsilateral side, for example, the blue circle. The positions on the other side of the black line are on the contralateral side, for example, the green circle. The figure is drawn by Louise Bohl, and the authors have permission to use it.

2.2 Hearing Mechanics

The ability to hear is complex, and a brief overview of AC and BC hearing will be explained in this section. Sound, what a person hears, is vibrations, and the ear converts these vibrations to electrical signals, which can be transferred to the brain [5]. Humans have two ways of getting sound into the inner ear, via the physical ear and the ear canal or utilising the skull bone and transmitting sound via the bones, avoiding the outer and middle ear, stimulating the cochlea directly. [4], [7]. The stimulation of the cochlea is essential because it converts vibrations to nerve impulses for the brain [5]. The entire frequency spectrum for a person is around 20-20000 Hz, but the range between 500-5000 Hz is the frequency heard most clearly [5].

Air conduction is the way of hearing most people are familiar with when it comes to understanding the concept of sound. A factor could be that the most visible parts of the ear have the function of converting air-conducted sound [5]. AC starts with the sound waves, alternating pressure regions moving in one direction, transmitted through the air, and vibrating objects are the source of sound waves [5]. The pathway of the conversion starts with the outer ear and the pinna [5]. The outer ear funnels sound waves into the ear canal, which directs them to the TM, and the alternating pressure regions make the TM vibrate, which is the last step in the conversion to vibration to nerve impulses to the brain [5].

Bone conduction is the second way for the cochlea to interpret sound [4]. Vibrations from the skull bone, skin, cartilage, fluids, and soft tissue all contribute with vibrations affecting the cochlea, which make us comprehend sound [4]. The phenomenon of BC hearing can be experienced when a human records their own voice, and the recorded sound is dissimilar to the humans' understanding of what they sound like [4]. The recording only records AC sound, but the person hears AC and BC sounds [4]. The paths the vibrations travel to the cochlea and basilar membrane were uncertain for some time [4]. However, recent studies (2005) have shown different ways for the vibrations to go from the skull bone to the inner ear and seven ways are known today, and five of them are essential [4].

The first pathway occurs because the vibrations from the skull physically disfigure the ear canal; therefore, this causes the air and therefore the TM to move in the ear canal and sound is created [20]. If the outer ear is dysfunctional, for example, the outer ear is sealed, this pathway of BC sound will be affected [4], [20]. A closed ear canal will lead to occlusion, and this pathway will impact the lower frequencies [4], [20]. In the case of an open ear canal, some sound will escape from the ear [4].

The second pathway emerges from the fact that the vibrations in the head affect the middle ear and the TM [20]. The vibrations from the cranium convert to sound pressure, and the TM is affected and sends signals to the cochlea [20]. Frequencies of approximately 2.5 kHz are affected by this pathway [20]. The third appears because the cochlea fluid's will be exposed to inertial forces when exposed to bone vibrations [20]. The fluids are regarded as incompressible, and the fluid will move between the round and oval windows and create a wave, and this wave travels on the basilar membrane [4]. This pathway is considered the most impactful for an average hearing person, and depending on what kind of dysfunction, this pathway could have various impacts [20]. Frequencies under 1 kHz have the most involvement in this pathway [20]. The fourth pathway occurs because the walls in the cochlea expands and compresses due to vibration, and this causes the cochlea fluids to move since the cochlea walls are moving [20]. It affects frequencies under 4 kHz along with 4 kHz [20]. The last pathway is that the cerebrospinal fluid can transfer sound pressure to the fluids in the inner ear, which will create sound [20].

2.2.1 Bone Conduction Stimulation

There are several ways to stimulate BC, both natural and artificial [21], [22]. Speaking creates vibrations in the mouth, teeth, and vocal cords, which propagate to the cochlea via the skull bone [21], [22]. BC transducers can create an artificial BC sound, sending the transducer's vibrations directly into the skull bone [21].

2.3 Hearing Loss

Hearing loss can be categorised into two primary sections: sensorineural and conductive hearing loss [23]. It is called mixed hearing loss if both conductive and sensorineural are present [24]. Another type of hearing loss are non-organic, where the patient's hearing ability and the hearing threshold are different [25]. Injury to the brainstem, brain, and nervous system can also lead to hearing loss [22]. Low, mid and high-frequency loss is in the range of (250-500 Hz, 1000-2000 Hz, and 4000-8000 Hz) [26].

Conductive hearing loss is when a blockage or dysfunction affects the outer or middle ear, making the sound unable to go into the ear [6]. Comparing the hearing thresholds for AC and BC can be used to diagnose conductive hearing loss since the AC threshold will be affected because of the blockage or malfunction, but the BC sound will not be affected due to the fact that the sound can still travel via the skull bone to the cochlea [6], [22], [27]. Hearings aids exist for conductive hearing loss, and mainly BC aids are used [22].

If the auditory nerve, cochlea, or central nervous system is damaged, it is called sensorineural hearing loss [23]. Sensorineural hearing loss can be caused by presbycusis, head injury, and Meniere's disease [23]. Analysing the AC and BC hearing thresholds can determine if a patient has sensorineural hearing loss because both thresholds will be affected [22], [27].

2.3.1 Hearing Tests

In a pure-tone audiometry the hearing range of 250-8000 Hz can be tested [26]. When AC and BC sounds are tested, a tone is sent via headphones or a bone transducer [26]. The hearing threshold at a specific frequency is the lowest sound the subject can hear 50% of the time [26]. Examples of other hearing tests include, for example, middle-ear compliance and stapedius reflex thresholds [26].

2.4 Sound Units

Sound can be measured and analysed with different units; decibel (dB) hearing level (HL) and sound pressure level (SPL) will be used in this report [28]. The first unit, dB HL, stands for hearing level and measures a person's sound threshold, at what dB level a person stops hearing [28]. It originates from what an average person hears at different frequencies [28]. If a person has a hearing threshold of -20 dB HL at 4 kHz, this is 20 dB lower than what an average person hears at this frequency, and if the threshold is 10 dB HL at 500 Hz, this is 10 dB higher at 500 Hz than the average person [28]. An audiometer can send out a specific dB HL and frequency, which can be used to test the dB HL [28], [29].

The unit dB SPL is used to understand if a sound has a high pressure or low by having a fixed value for the pressure [28]. By having a fixed value, a numerical value can be calculated, seen in equation (2.1) [28]. The fixed value P_2 is $20\,\mu\text{Pa}$ and P_1 is the measured pressure, which equal a value in dB when taking $20 \cdot log_{10}$[28].

$$dB_{SPL} = 20 \cdot log_{10} \frac{P1}{P2} \tag{2.1}$$

To convert dB SPL to dB HL, the reference equivalent threshold sound pressure levels (RETSPLs) need to be known [30]. The RETSPL values are available in the ANSI standards, and these are added together with the dB SPL value to receive the dB HL value [30]. In Table 2.1, the scale-values can be seen.

Table 2.1: The RETSPL values from [30]

Frequency (Hz)	500	1000	2000	4000	6000	8000
ANSI RETSPL (dB)	6.0	4.0	0.5	-4.5	4.5	13.5

2.4.1 Scale of Sound

Raising the signal by 3 dB is equal to doubling the power [28]. A 10 dB increase equals a doubling of what a person hears from the sound for almost the whole frequency spectrum [31]. The scale is only accurate if the sound is over 200-300Hz and above 40 dB [31].

2.5 Bone Conduction Hearing Aids

BCDs do not use the outer and middle ear, instead, the sound is transmitted straight to the cochlea with vibrations, using the skull bone as pathway [7]. Different methods have been developed over the last 60 years, including titanium screws, implanted transducers, softbands, along with others [7]. The two main categories for BCDs are skin-drive and direct-drive, according to Reinfeldt et al. [7], which the rest of this section is based on.

Skin-drive devices do not penetrate the skin and can either be attached over the skin or be implanted under the skin [7]. One of the first skin-drive techniques used on the market was a softband around the head to attach the device to the desired spot, called conventional. Another technique, passive transcutaneous, has an implanted part with a magnet and a screw. The screw is attached to the skull bone and connected to a magnet under the skin. Another magnet has an audio processor attached and is placed on the skin, attaching to the inside magnet, and sending vibration via the skin. Skin-drive devices have issues transferring sounds at high frequencies due to the skin suppressing the signal. The device also needs high pressure between the magnets and the skin because higher pressure equals better transmission, which can cause unpleasantness for the patient. A technique called Adhear from MED-EL uses an adhesive material which can be used as an attachment method for transcutaneous vibration devices [11], [15].

Direct-drive devices send signals straight to the skull bone, bypassing the skin, handling higher frequencies better than skin-drive devices [7]. BAHAs (percutaneous) penetrate the skin with a screw attaching to the skull bone. On the screw, a sound processor is connected outside the head and behind the ear, sending vibrations directly to the skull bone [7], [31]. One benefit of BAHAs is that the skin is not exposed to pressure, as with skin-drive devices. One disadvantage of BAHAs is the infection risk around the screw and that the patient needs to take care of the wound for the rest of their life. Conductive hearing loss, mixed hearing loss, and SSD are indications for the use of BAHAs.

The second direct-drive system described is active transcutaneous, which has an implanted part under the skin [7]. On the outside of the skin is an audio processor sending an electrical signal to the implanted part. The implanted part is a transducer which receives the signal from an inductive link and sends vibrations into the skull bone. The audio processor is kept in place by magnets.

2.5.1 Devices Used in the Study

The Baha Intenso is a sound processor from Cochlear, with a transducer sending vibrations, a microphone, and an amplifier [32]. It was introduced to the market in 2007, and it can be attached either as a direct-drive percutaneous device in the skull bone or as a skin-drive device using a softband around the head [7], [16], [32]. When released, it was superior to the other hearing devices on the market in terms of highest maximum output and gain, mainly due to its phase-eliminating algorithm [32], [33]. It has three different modes called "E", "1", and "2" [34]. The first program, "E", needs an attachment to function [34]. The second program, "1", is used in a regular hearing session and the last program, "2", is optimal in a noisy environment [34]. On the side of the Intenso, a wheel adjusting the volume between 0-3, with three being the highest, can be found [34].

The Radioear B81 is a transducer that is used for measuring BC hearing thresholds [35]. The B81 uses the balanced electromagnetic separation transducer (BEST) technique, which at lower frequencies gives a better signal (decreased harmonic distortion) than older devices such as the B71 [35], [36]. The transducer can be attached to the skin with the Radioear P-3333 steel spring headband and sends vibrations through the skin to the skull bone, like a skin-drive device [3], [7], [37]. Another improvement over the old device is that the B81 can handle more powerful hearing losses than its predecessor [38].

The B81 has low distortion and is limited at most frequencies by the maximum allowed operation voltage when testing its maximum output HL, but at some frequencies, it is limited by the total harmonic distortion (THD) [35]. When the B81 was introduced, it was intended to offer a low distortion alternative to the older B71, and because of this, the B81 was constructed with a similar frequency response and electrical impedance as the B71 [35]. For frequencies below 1500 Hz, the B81s maximum HL is 10.7 to 22 dB bigger in comparison with the B71, but at higher frequencies, it remained the same between the two [35]. The mean maximum HL can be seen in Figure 2.5 [35].

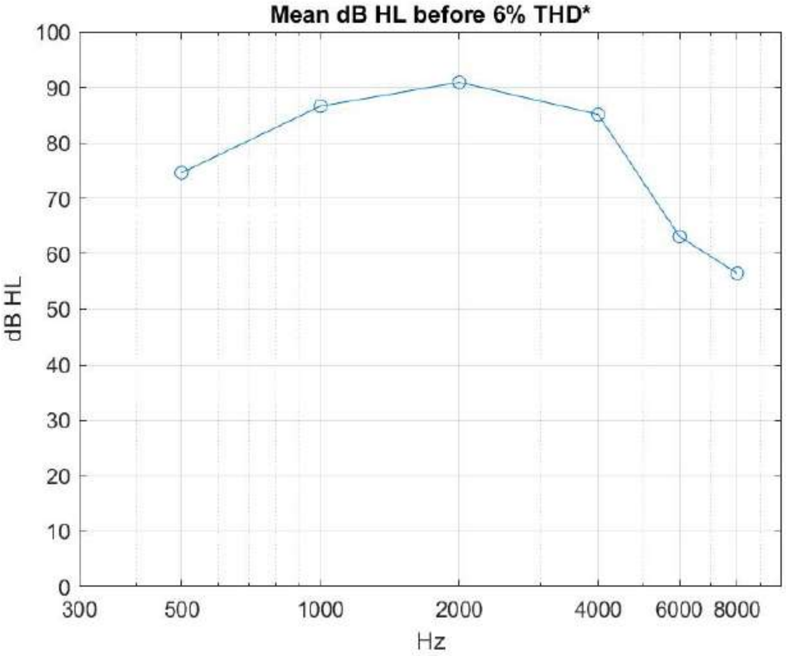

Figure 2.5: The maximum HL were raised until the THD was 6%, where * stands for: or the input voltage exceeded 6 V_{RMS} [35].

2.6 Skin Microphone

The SM used in this study developed at University of Alberta (Edmonton, Canada) is an electric condenser microphone, 66BB30 from Sonion, with an amplifier circuit consisting of an OPA172 from Texas Instruments, making up the measurement tool used in this study [19]. A brass metal casing incapsulate the SM, and inside the case is a yellow and white foam protecting the microphone from disturbance seen in Figure 2.6 [16]. The microphone has been modified for these types of measurements [16].

A condenser microphone works as a capacitor, usually cylindrical, using two parallel metal plates [39]. One is referred to as the diaphragm, which is thin and flexible, and the other as the back plate, which is stationary [39]. The diaphragm is thin and moves with the incoming sound, and this movement causes the voltage between the plates to fluctuate [39]. This fluctuation is in accordance with the incoming sound waves, thus converting the physical sound waves to an electrical signal [39].

Figure 2.6: The SM that is used in the study can be seen in the figure. The microphone is inside a brass casing with yellow and white foam and a hole for the microphone [16]. This construction improves the sound insolation for the microphone [16].

2.6.1 Earlier Studies with the Skin Microphone

Two earlier studies have been done with the SM, one focusing on using the SM as a verification method for BCD [16], [19]. The other study focused on objective measurements with the SM, which also can be used as a verification method for BCD, similar to the REM method for AC aids [16]. This study showed promising results using the SM in a clinical setup and was also verified by performing similar measurements on a skull simulator and an artificial mastoid [16]. In both studies, the SM was placed on the center of the forehead [16], [19].

2.7 10-20 Method

The 10-20 method is used for placing electrodes on the head for electroencephalography (EEG) measurement [40]–[42]. It acknowledges different-sized heads and uses easily found points on the head, such as the inion, the preauricular, and the nasion [40]. For example, the distance between the inion and nasion is measured, and electrodes are placed out, either 10% or 20% of the total distance and then 10% or 20% from the new point until reaching the other side's landmark [40]. The benefit of using percentages from the start to finish is that, in theory, the electrodes are placed in the same place on different-sized heads [40]. The method uses 21 electrodes around the head [41].

The first letters in the position name derive from the frontal pole (Fp), frontal (F), central (C), temporal (T), parietal (P), and occipital (O), indicating a specific place on the head [42]. After the first letters, a number or letter indicates a more specific position, such as the right hemisphere and lateral position on the right hemisphere etc. [42]. Another example is zero (z), which is the name of the middle positions of the head from the nasion to inion, therefore called the zero position [42].

2.8 Maximum Power Output and Noise Floor

Maximum power output (MPO) is the maximum power a device can amplify, and the signal gets saturated over this level [16]. The signal will no longer increase in value because the saturated level is reached [43]. Hearing test measurements require a quiet environment because the noise can affect the result [44]. Noise floor (NF) is the term used to describe the noise level in the test environment before the test is carried out [44]. The noise could be present because the transducer produces noise, electrical equipment, and amplifiers [44]. If the measured data is below the NF, it can cause insufficient data [44].

2.9 Statistical Methods

Standard deviation is a statistical method used if the data is assumed to be normally distributed [45]. The standard deviation (SD) can be used to analyse the data, as seen in equation (2.2) [45]. Where N is the sample size, M is the sample mean, and X_i is the data points [45]. The data is normally distributed if the data has a bell shape form and can also be analysed by a QQ-plot, and SD explains how far from or how near the sample points are to the mean [45]–[47]. If the data is normally distributed, 95% of the data points will fall inside the interval of 2 SD [48].

$$SD = \sqrt{\frac{\Sigma(X_i - M)^2}{N-1}} \tag{2.2}$$

Median absolute deviation (MAD) is a non parametric statistical method to find the interval between the median and sample values of robust sample points [49], [50]. The MAD method is more robust to outliers compared to other methods such as the SD, because the method uses the median function [51], [52]. If the data is not normally distributed, MAD can be used to find relevant information about the data [50]. The equation for MAD is seen in equation (2.3), where X_i is the sample points and the $median_1$ is the median for all data points and $median_x$ is the median value of the array made from $|X_i - median_1|$ [50], [51].

$$MAD = median_x(|X_i - median_1|) \tag{2.3}$$

Sample size can be calculated for a group when two different sample groups, 1 and 2, have a specific error type 1 value and a specific power value seen in equation (2.4) [53]. The first variable z($\alpha/2$) is the standard normal distribution for the ($\alpha/2$) quantile, and α is type 1 error and β type 2 error [53]. The equation for the power, which uses the type 2 error, is seen in equation (2.5) [53]. A relation between the number of samples between the two sample groups is the variable k seen in equation (2.6) [53]. The variance σ^2, the mean value μ, and the sample value n is seen in equation (2.4) [53].

$$n_2 = \frac{(z_{\frac{\alpha}{2}} + z_\beta)^2 \sigma^2 (1 + \frac{1}{k})}{(\mu_1 - \mu_2)} \tag{2.4}$$

$$1 - \beta \tag{2.5}$$

$$k = \frac{n_1}{n_2} \tag{2.6}$$

3

Methodology

The methodology chapter is divided into six sections, literature study, calibration, trial 1, trial 2, final measurement and analysing the data in MATLAB. The test environment consists of a sound-isolated room of 16 m^3, a speaker (approximately 120 cm from the subject's forehead) and a B81 transducer connected to an audiometer in a separate room. An Agilent signal analyzer is in the same room as the audiometer, making it possible to manage both devices simultaneously without entering the sound-isolated room. Two different devices was used in the SM measurements; the audiometric transducer B81 and the Intenso hearing aid.

Reading and analysing earlier research papers was the first step in this study. The second step was to calibrate the SM. The other devices, such as the Agilent and audiometer, were already calibrated or calibrated automatically when necessary. After this, the first positions and signals were tested and evaluated on the two test subjects. A tone signal with different frequencies was chosen to be the signal during the trials. New signals and a new attaching arrangement were built for the next trial, and the data was again analysed for the final measurement. The most promising positions from trials 1 and 2 was continued with in this stage. Factors such as a similar result with the device on both the right and left sides for the same positions, signals over the NF for all frequencies, and different mean and SD values. In the last stage, the SM was tested on four subjects, fewer positions, and repeatability measurements, testing the signals multiple times. Thereafter, all data was analysed in MATLAB. In Table 3.1 and Table 3.2 present the hearing threshold for the subjects.

Table 3.1: The table shows how the four test subjects hearing was between 250-8000 Hz, left ear. If the hearing threshold was 20 dB HL or under "ok" and "X" if the threshold was over 20 dB HL.

Right Side	Subject 1	Subject 2	Subject 3	Subject 4
250 Hz	ok	ok	ok	ok
500 Hz	ok	ok	ok	ok
750 hz	ok	ok	ok	ok
1000 Hz	ok	ok	ok	ok
1500 Hz	ok	ok	ok	ok
2000 Hz	ok	ok	ok	ok
3000 HZ	ok	ok	ok	ok
4000 Hz	ok	ok	ok	ok
6000 Hz	ok	ok	ok	ok
8000 Hz	ok	ok	X	ok

Table 3.2: The table shows how the four test subjects hearing was between 250-8000 Hz, right ear. If the hearing threshold was 20 dB HL or under "ok" and "X" if the threshold was over 20 dB HL.

Right Side	Subject 1	Subject 2	Subject 3	Subject 4
250 Hz	ok	ok	ok	ok
500 Hz	ok	ok	ok	ok
750 hz	ok	ok	ok	ok
1000 Hz	ok	ok	ok	ok
1500 Hz	ok	ok	ok	ok
2000 Hz	ok	ok	ok	ok
3000 HZ	ok	ok	ok	ok
4000 Hz	ok	ok	ok	ok
6000 Hz	ok	ok	X	ok
8000 Hz	ok	X	X	ok

3.1 Literature Study

A literature review was conducted to find relevant information on the topic of this study. Google Scholar and IEEE were primarily used in this thesis as search engines. Books, doctoral theses and data sheets were also considered in the literature review when relevant. Search words were used, such as "bone conduction", "bone conduction device", "air conduction", "hearing aid", "sound", and "decibel". However, new scientific reports were the primary focus of sources in the literature review and only information in English and Swedish was considered.

3.2 Calibration

The SM was calibrated in four steps to find the relation between the SM and a reference microphone (RM) in dB SPL. These calibration values were used for all measurements during the study, and the four different steps are explained below.

1. The SM was calibrated using a RM and a sound calibrator (G.R.A.S 42AB) seen in Figure 3.1, where the sound calibrator was the black chamber and the RM was the grey cylinder. The sound calibrator sends out exactly 114 dB SPL at 1000Hz. Placing the RM into the calibrator gives an exact value of 114 dB SPL at 1000 Hz. The RM voltage was measured with the Agilent signal analyzer 35679A in a linear spectrum, and the voltage value at 1000 Hz, 114 dB SPL, was used as the constant k_1. The G.R.A.S 42AB got powered from the Brüel and Kjær type 2804 power supply. The idea was to use the RM, to find the difference between the SM and RM at a specific frequency, and then add this difference to the SM at that frequency.

Figure 3.1: The figure shows a G.R.A.S 42AB, the black cylinder on the table was the speaker chamber producing 114 dB SPL at 1000 Hz and the grey part was the RM. The value the RM obtains in the chamber was used in the calibrations.

2. A new constant k_2 was needed to be calculated to convert from dB to voltage in the expression. In equation (3.1), constant k_2 was calculated, where the dB SPL level was 114 dB SPL.

$$k_2 = (10^{(\frac{dB}{20})}) \tag{3.1}$$

3. An Anechoic Test Chamber type 4222 "the egg", produce a sound level in a frequency range from 100-10000Hz from speakers inside the "the egg", using the power amplifier RB-976 MKII. Placing the RM inside "the egg", gives an output voltage for every frequency (RMV_1), dividing this with k_1 and, multiplying with k_2, gives the correct value ($RM_{correct}$) for all frequencies for the RM seen in equation (3.2).

$$RM_{correct} = \frac{RMV_1}{k_1} \cdot k_2 \tag{3.2}$$

4. The last step was to make a relation between the $RM_{correct}$ and the SM. Placing both microphones in "the egg" doing a frequency sweep at a specific dB seen in Figure 3.2. Dividing the $RM_{correct}$ value with the SM gives the calibrated condition ($calibrated_{condition}$) for the SM seen in equation (3.3). The measurement was repeated four times and the median value of these four values was taken. The calibration values were then used to convert the dB_{Vrms} values from the Agilent to dB SPL.

$$calibrated_{condition} = \frac{RM_{correct}}{SM} \tag{3.3}$$

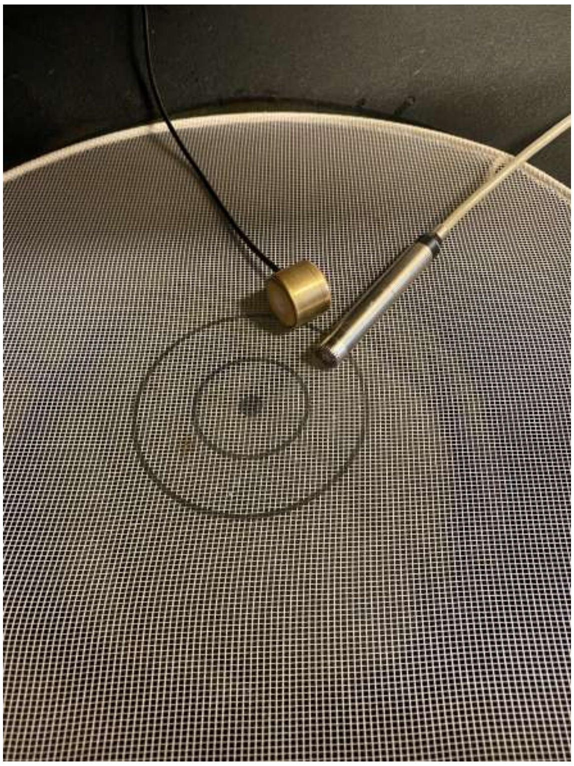

Figure 3.2: RM and SM placed inside the egg, to calculate the difference between them under one frequency sweep. This picture illustrate step 4 in the calibration step.

3.2.1 Maximum Output of Intenso

To determine the saturation level of the Intenso, it was placed inside the Verifit Skull Simulator, where it was stimulated with 60, 70 and 90 dB SPL. From this, the saturation level was found, which, together with the RETSPLs, determined the maximum dB HL level that could be used with the Intenso. The values can be seen in Figure A.1 in the appendix.

3.3 Trial 1 Measurements

In the first trial, the measurements were done on subject 1 and 2 with normal hearing, i.e. maximum 20 dB HL in all audiometric frequencies except for subject 2 at 8 kHz, right side with a hearing threshold over 20 dB HL seen in Tables 3.1 and 3.2. The average age of the two test subjects was 24 years. In the first trial, 13 positions were tested to investigate if any places around the head exceeded the NF and showed promising result. The setup used in trial 1 using the B81 transducer over the skin is shown in Figure 3.3. The audiometer AC40 (Interacoustics A/S, Assens, Denmark) shown in Figure 3.4 was connected to the B81 transducer via a wire, and the B81 transducer sent out out vibrations programmed on the audiometer. The audiometer had a frequency spectrum between 250-8000 Hz. The transducer was held into place with the Radioear P-3333 steel spring headband and placed on both the right and left side of the ear at the temporal bone. The SM was connected separately with a softband and via a cable to an amplifier, amplifying the signal. The next step was to connect the amplifier to an Agilent signal analyzer, where the measured data could be displayed, and this data was transferred into MATLAB for further analysis. Peltor hearing protection was used over the SM to protect from air conducted sound leakage from the speakers, electrical equipment etc.

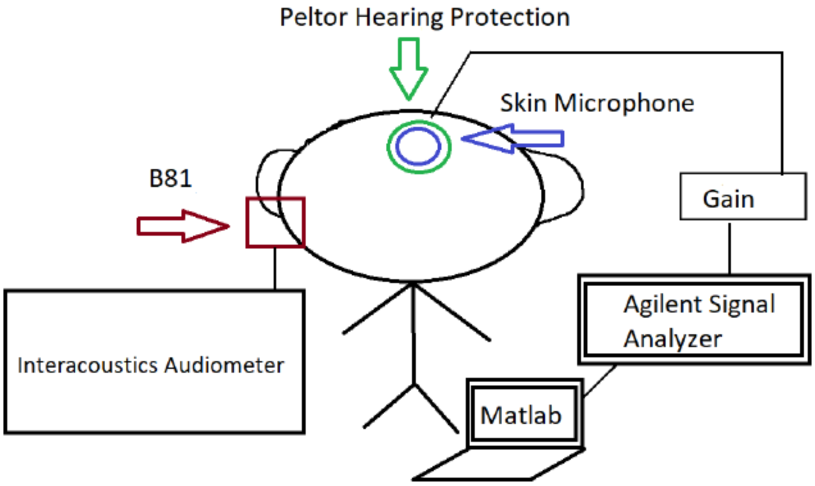

Figure 3.3: Setup for the trial with the B81 transducer, with the SM placed on the forehead. The signal goes from the audiometer to the B81 transducer, and the transducer transmit vibrations via the skull to the SM and the signal was then transmitted further to the Agilent to be analysed.

Figure 3.4: The audiometer AC40 (Interacoustics A/S, Assens, Denmark) used to simulate signals in all the trials. The audiometer could simulate different frequencies and dB HL levels for the B81 transducer and speaker inside the insolated room.

The other part of the measurements was done with the skin-drive device Intenso from Cochlear instead of the B81 transducer. The setup was similar for the SM but with some changes for the Intenso device compared to the B81 transducer seen in Figure 3.5. The Intenso hearing device cananot be programmed via the audiometer to produce a particular sound as with the B81. Instead using speakers to send out a particular sound connected to the audiometer, the microphone in the Intenso apprehends this sound and therefore sends out vibrations. The speaker HECO ODEON 100 (frequency response 40-32000 Hz) was placed approximately 120 cm from the front of the subject's forehead and the Intenso device was held in place with a softband. The settings on the Intenso was set to gain 2 (on a scale between 0-3) and listening mode 2, especially good at removing noise and other settings were set to maximum gain. The Intenso drains batteries quickly, and the battery was changed every week to make the measurement with the Intenso as even as possible.

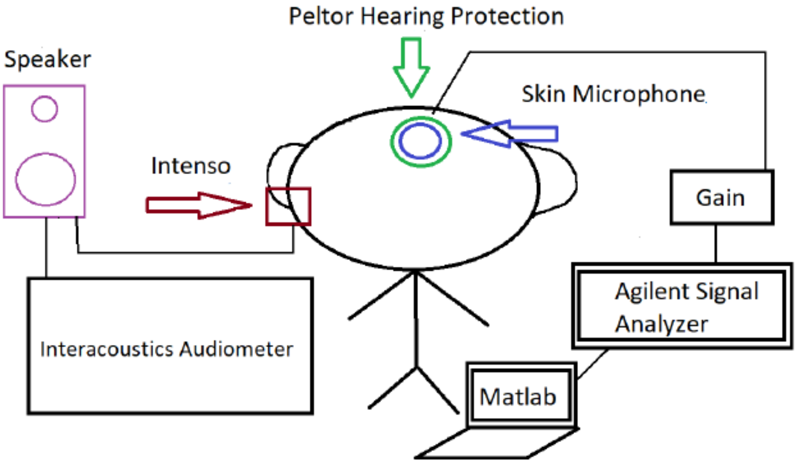

Figure 3.5: Setup for the trial with Intenso, with the SM, placed on the forehead. The signal goes from the audiometer to a speaker, sending a tone signal that the Intenso microphone converts to vibrations. The vibrations proceed from the Intenso via the skull to the SM and then to the Agilent to be analysed.

The audiometer sends out signals with different frequencies and dB HL. In the first trial, three frequencies, 500, 1000, and 4000 Hz, and two dB values, 30 and 40 dB HL, were tested with the B81 transducer. The Intenso was analysed with 500, 1000, 4000 Hz, and 70 dB HL. The different dB HL for the B81 and Intenso and the chosen frequencies are discussed in section 5.2.

Different positions for the SM were tested, and placing the B81 transducer and Intenso on both the right and left side behind the ear. Twelve positions were tested in this first measurement, five around the ears, five on the forehead, and two on the head. Full disclosure of the positions can be seen in Figures 3.6, 3.7 and 3.8. Placing the SM in trial 1 did not need any measurement tool. Instead, known landmarks were used, such as the eyebrows, eyes, cheekbones, top of the head, inion, temporal bone and the temples. The NF was measured with the SM placed in the middle of the forehead without ear protection and the door open, which made the room not soundproof.

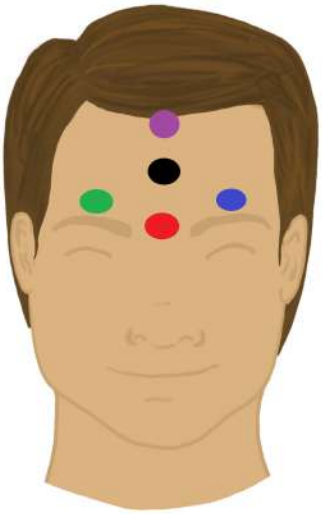

Figure 3.6: The different positions of the SM from the front of the head for trial 1. Green and blue were approximately 1 cm over the eyebrows and in the center of the eyes. Red, black, and purple were all in the middle of the forehead over the nose, with red between the eyebrows. Black was between the height of the eyebrows and the hairline, and purple at the hairline. The figure was drawn by Louise Bohl, and the authors have permission to use it.

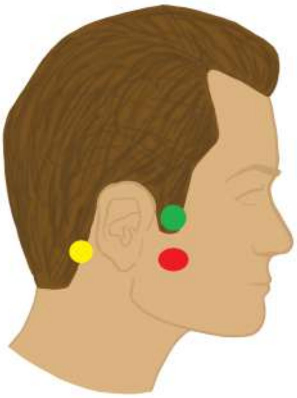

Figure 3.7: The different positions of the SM from the side of the head for trial 1. Green was on the temple, and red was on the cheekbone. Yellow was both the position for the temporal bone and the B81 or the Intenso, depending on which side was tested. If the B81 were on the right side, the temporal bone position was on the left side. The figure was drawn by Louise Bohl, and the authors have permission to use it.

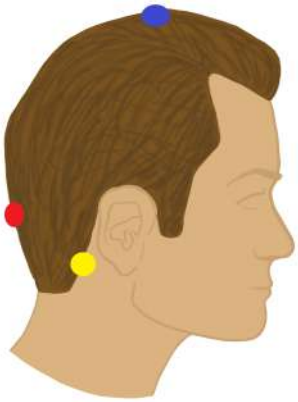

Figure 3.8: The different positions of the SM on the head for trial 1. Blue was the position for Cz, red was the inion, and yellow was the position for the B81 or the Intenso. The figure was drawn by Louise Bohl, and the authors have permission to use it.

Analysing the output from the SM was done with an Agilent signal analyzer. Sending out a signal via the audiometer to the B81 transducer or speaker and was thereafter registered by the SM. As mentioned in the background section 2.6, the microphone measures BC sound. A frequency sweep was done on the Agilent to find the output signal from the audiometer, sweeping from 100 Hz to 10000 Hz. Two plots, one showing mV_{rms} at a specific frequency and one showing dB_{Vrms} by converting the voltage seen in equation (3.4). The value in dB_{Vrms} and adding the calibration value for the specific frequency gives the result in dB SPL. The data was then analysed to find the positions with the most promising result, these positions were kept to trial 2, and the other positions were not investigated further.

$$dB_{Vrms} = 20 \cdot log_{10}(Vrms) \tag{3.4}$$

3.3.1 Building a New Attaching Arrangement

A new attaching arrangement for the SM inside the earmuff was created by doing a Computer-Aided Design (CAD) model in the Autodesk Fusion 360 CAD software. The attaching arrangement was designed for the SM to be centred in the earmuff and stick out enough to have good pressure against the skin while not sticking out too much so the earmuff cannot cover the SM completely and not protect against sound leakage. The CAD model was sliced in Ultimaker Cura and 3D printed on a Creality Ender 6 in black polylactic acid.

Figure 3.9: The CAD model of the attaching arrangement in Fusion 360.

Figure 3.10: Final construction of the earmuff. The softband goes inside and under the attaching arrangement to apply pressure to the SM to get a clean connection between the SM and the skin. The softband can be adjusted with a clip.

3.4 Trial 2 Measurements

In trial 2, the measurements were done on subjects 1 and 2, and a similar setup was used in trial 2 as in trial 1, but with some modifications. In this trial, all testing was done with the new attaching arrangement designed to make it easier to place the SM on the head together with the earmuff. In trial 1, positions on top of the head were difficult to measure because the Peltor ear protection headband was too small. This problem was eliminated with this new design. In trial 2, some parameters were changed from trial 1. More frequencies were tested 2000, 6000, and 8000 Hz was added together with the frequencies from trial 1 (500, 1000 and 4000 Hz). All together six frequencies were tested in trial 2. B81 was measured with 40 dB HL and Intenso with 70 dB HL. However, at 8000 Hz, the dB HL was set to 30 dB HL when using B81 because the test subjects experienced 40 dB HL as unpleasantly high. Moreover, the maximum output of the audiometer was limited to 58 dB HL at 8000 Hz and therefore, 50 dB HL was chosen for 8000 Hz since only 10 dB HL steps were used in the study. The B81 and Intenso were tested on both the right and the left side of the head. The settings on B81 and Intenso were the same as in trial 1. Positions from trial 1 with promising results were tested with the new frequencies in trial 2 for further inspection.

As seen in Figure 3.11, eight new positions were tested on the top of the head and one on each ear. The implemented method to find the location of the positions was inspired by the EEG 10-20 method, explained in section 2.7. Finding the positions for F3 and F4, the distance between the nasion and inion was measured, then 30% of this distance from the nasion was the coordinate on the y-axis. The position on the x-axis requires finding 30% percent of the distance between the nasion and inion starting at the nasion for both the left and right sides of the head, giving the positions of F7 and F8. Using 25% and 75% of the total distance between F7 and F8 from F7 gives the position of F3 and F4.

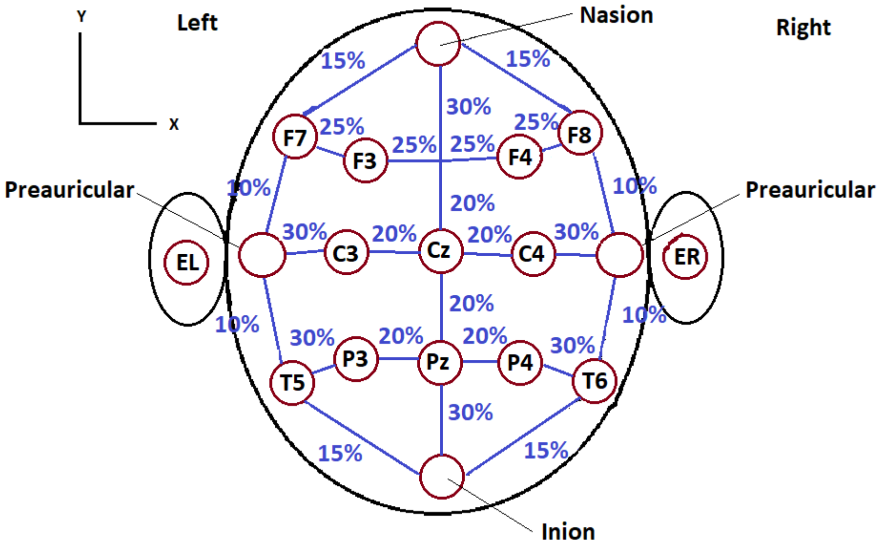

Figure 3.11: Positions for the SM in trial 2 To find the different head positions for the SM, landmarks such as the nasion, inion, and preauricular were used as starting points when measuring. Different percentages from these three points were used to calculate the eight positions on the head marked with red circles. In trial 2, the SM was also tried on the left (EL) and right (ER) ear.

Positions C3, Cz, and C4 were 50% of the distance between the nasion and inion on the y-axis. The preauricular was then used to find the location on the x-axis. The total distance between the preauricular was calculated, and C3 was 25%, Cz was 50%, and C4 was 75% between the preauricular starting from the left side. Placing the SM on the left and right ears was the positions EL and ER.

The last three positions, P3, Pz, and P4, were on the back of the head. The positions' y-coordinate was 70% of the total distance of the nasion and inion starting at the nasion. The x-coordinates for P3, Pz, and P4 starts with taking 30% of the distance between the nasion and inion. Measuring on the right, respectively, the left side on the head starting at the inion gives the location of T5 and T6. Using 25%, 50% and 75% of the total distance between T5 and T6 starting at T5 gives the location on the x-axis for P3, Pz and P4.

When the data was analysed, the position names were changed to correlate with the B81 and the Intenso positions. For simplicity, a position called "Ipsilateral..." means that the B81 or Intenso was on the same side as the SM. For example, placing the B81 on the right side and the SM on the right eyebrows was called "Ipsilateral eyebrow". When the position was called " contralateral...", the SM, and the B81 were on the opposite side. For example, placing the SM on the right side and B81 on the left eyebrows, the position of the SM was "contralateral eyebrow". This was the case for the eyebrows, cheekbone, temple, F3, F4, C3, C4, P3 and P4. If the position was placed in the middle, such as the Pz, it will be called medial. If the position is in the center, like C4 and C3, the position was called central. Another change was made when measuring the positions from trial 2. Instead of having a letter and a number in the name, anterior, central and posterior was used together with ipsilateral and contralateral to explain the position. Positions on the front, middle and back were called anterior, central and posterior, together with which side ipsilateral, contralateral or medial. The position Cz, between eyebrows, center forehead, hairline forehead, inion, EL, ER and temporal bone will have the same name.

3.5 Final Measurements

Seven positions were tested in the final measurements, three from trial 1; center forehead, ipsilateral eyebrow and temporal bone. From trial 2, four positions were chosen; ipsilateral anterior, ipsilateral central, ipsilateral posterior and Cz. Center forehead used a different location method in the final trial, measuring 4 cm above the nasion for the all subjects. The measurements were done on four subjects, with an average age of 32, and the hearing threshold for the subjects are displayed in Tables 3.1 and 3.2. The new attaching arrangement described in the section 3.3.1 was used in all measurements. The B81 transducer and Intenso hearing device were the devices used. The B81 was tested with 40 dB HL except for 8000 Hz with 30 dB HL and Intenso with 70 dB HL except for 8000 Hz with 50 dB HL. Three different tests were done with the devices and SM in the final measurement and the same settings for the B81 and Intenso as in trial 2 was used:

1. The SM was placed on each of the seven positions, and either the B81 or Intenso was on the left or right side of the head for a total of 28 measurements. In each measurement, six different frequencies were analysed with a tone signal. The frequencies tested were 500, 1000, 2000, 4000, 6000 and 8000 Hz. The test was performed on four test subjects. The hearing threshold for the subjects can be seen in Tables 3.1 and 3.2.

2. The second test examined on test subject 1 investigated how robust the SM was for repeatability measurements when the equipment was not removed. The same frequency was repeated five times for each position using the B81 on the right side without removing the equipment. Next, B81 on the left and the Intenso on the right and left sides were tested without removing the equipment during measurement.

3. In the third test, step 1 was repeated five times for test subject 1. The equipment was removed and then placed again on the test person. The B81 and Intenso were tested on both the right and left sides for all tests, and the six frequencies from step 1 were measured.

One change from trials 1 and 2 was the frequency sweep on the Agilent. One sweep from 100-10000 Hz was done in trials 1 and 2 for each measurement. In the final measurement, two sweeps were used to reduce time as the time it took for the sweep to reach the higher frequencies was long. The range for the sweeps was now 100-10000 Hz and 5000-10000 Hz. The first sweep was used for 500, 1000, and 2000 Hz signals, and the second for 4000, 6000, and 8000 Hz signals. The calibration value was then used to get the result in dB SPL, and the same setup was used as in trial 1 and 2 seen in Figures 3.3 and 3.5 except for these modifications.

3.6 Analysing Data in MATLAB

To process the data, MATLAB was used with functions such as mean, median, and semiologx. The data was stored in fields and struct for organisation and easy access. Different methods were used, such as investigating the BCD on both the right and left sides, inspecting the raw data for all measurements, and taking mean, median and analysing the SD. All values were with the calibration added on.

3.6.1 Trial 1 and 2

The dB SPL values were plotted and analysed for both right and left-placed BCD for 30, 40, and 70 dB HL (50 dB HL for 8000 Hz for the Intenso) and 500, 1000, 2000, 4000, 6000 and 8000 Hz. The amplitude, the evenness in the data, right and left side and similarity between 30 and 40 dB HL graphs were examined for the B81. For the Intenso the amplitude, the evenness in the data and right and left side was explored. A second method took the difference of the data from when the B81 or the Intenso was on the right and left side for each dB HL level and frequency; this data was analysed in two different ways, with the first one with most impact. Notice that when subtracting dB SPL from dB SPL, the unit will only be dB. This was because dB SPL were in logarithmic scale.

1. The mean value was analysed from the data for all positions and a lower mean value indicating similar behaviour for the position when using the BCD on the right and left side.

2. The second method evaluate the MAD median method and a smaller value indicating a more robust data and if the mean was high and MAD median low, indicating an outlier in the data. If both the MAD median and mean were high, the right and left side were not similar.

3.6.2 Final Measurements

In the final measurements, the first test did compare the mean and SD when each side was analysed as one measurement for the four subjects, which is equal to eight measurement for each device. A second test investigated how many samples were needed to get a type 1 error with 5% and a power value at 0.95 using equation (2.4) for the same data as test 1. This was done by comparing the center forehead position with the other position of interest. The third test was the identical MATLAB methods as in trials 1 and 2 were the raw data was investigated, the evenness in the data, the amplitude and comparing the sides with each other. A fourth test was done analysing step two and three from section 3.5, testing the sensitivity and repeatability of the SM and the setup and the SD and mean value were analysed for all position and both devices.

4

Result

All data from trials 1, 2, and the final measurement are below the MPO for both the B81 and Intenso, explained further in sections 2.8 and 3.2.1. In the result chapter, only a few positions are displayed. However, all data have been considered in the calculations and in the motivations when removing or adding a position to the subsequent trial.

4.1 Trial 1

Figure 4.1 shows the data points from the first measurements at 30 and 40 dB HL for the B81, subject 1 and the left ear. One position from each group, forehead (center forehead), ear (temporal bone), and head (inion), is plotted together with the NF. The value for each position is shown for 500, 1000, and 4000 Hz. The center forehead position at 500Hz for 30 and 40 dB HL has a difference of around 10 dB, which also can be seen at 1000 Hz and 4000 Hz. For the temporal bone at 500 Hz a difference of approximately 9 dB can be seen when changing the input sound level between 30 and 40 dB HL. The same similarity can be seen at the frequencies 1000 Hz and 4000 Hz. This is also true for the inion, with a difference of around 10 dB SPL between 30 and 40 dB HL for all frequencies. Using 30 or 40 dB HL, gives the result an difference of around 9-10 dB for both positions. The data in Figure 4.1 are over the NF. The other nine positions' data for subject one, right ear, and data from subject 2 show similar results with a linear dB offset when using 30 and 40 dB HL.

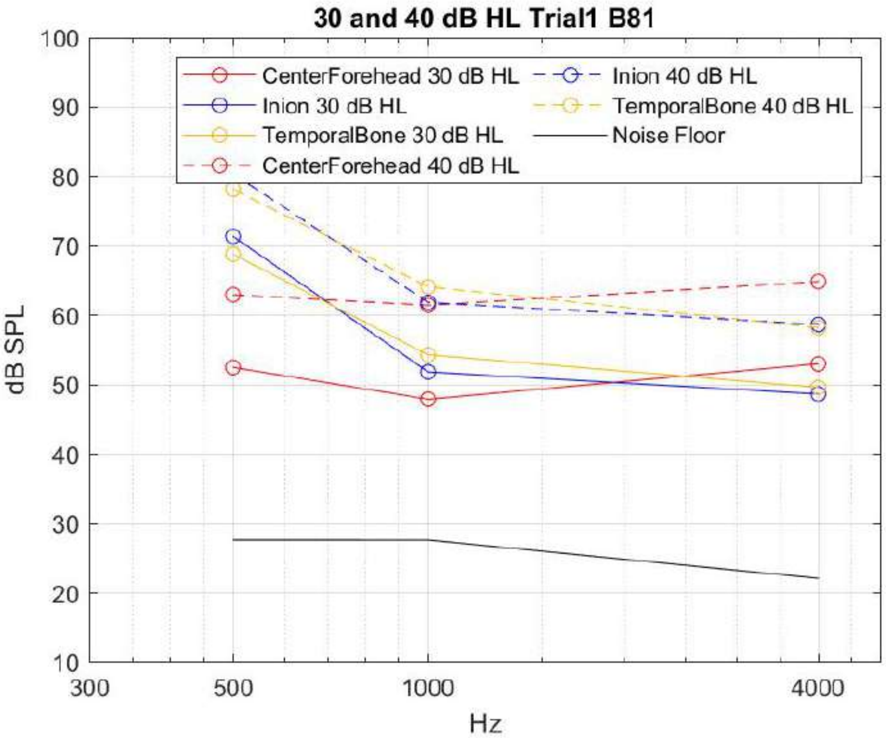

Figure 4.1: Result from the B81 at 30 and 40 dB HL, subject 1, at 500, 1000, and 4000 Hz. One position from the forehead (center forehead), one from the ear (temporal bone) and one from head (inion). A linear offset between 30 and 40 dB HL for the three frequencies and the three positions can be seen.

The result from the Intenso can be seen in Figure 4.2 for subject 1, 70 dB HL and left ear. One position from each group is chosen, center forehead, temporal bone, and inion. The data are above the NF with at least a minimum of 25 dB SPL, and center forehead is approximately 3 dB SPL over temporal bone at each frequency. The data from the inion position does not follow the other two positions. Instead, the values decrease for higher frequencies. The inion has the highest value at 500 Hz but the lowest value at 1000 and 4000 Hz.

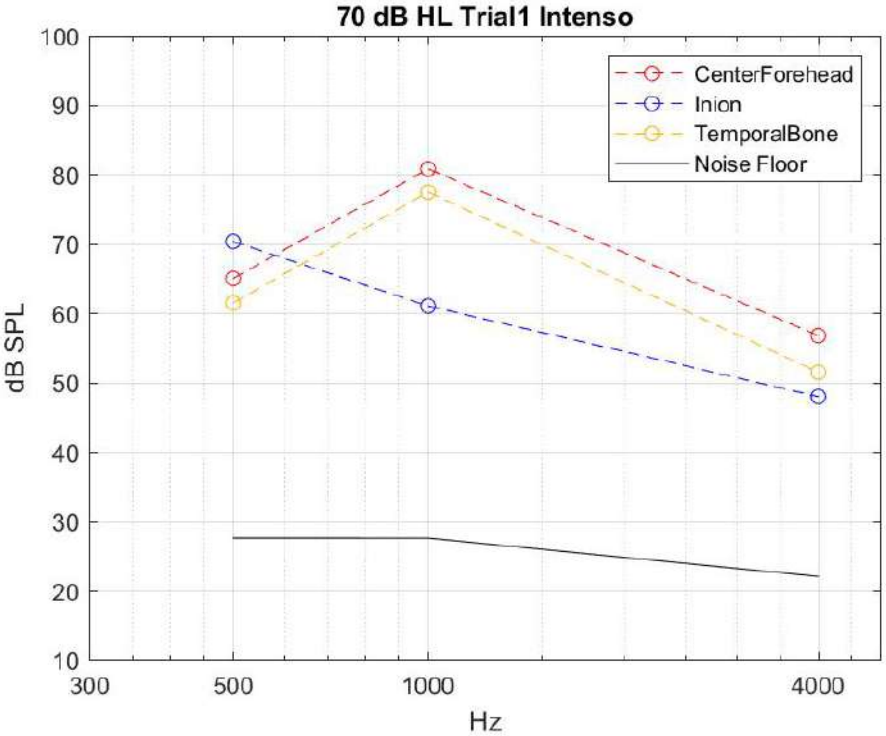

Figure 4.2: Result from Intenso at 70 dB HL, subject 1, at 500, 1000, and 4000 Hz. One position from the forehead (center forehad), one from the ear (temporal bone) and one from head (inion). The center forehead and temporal bone show similar characteristics, and the inion position decreases in value for higher frequencies.

4.1.1 Difference Between Sides

The raw data is further analysed and compared for each position by subtracting the sides for each measurement value for all frequencies, which indicates if there is a difference using the Intenso or B81 on the left or right side of the head. The mean value is investigated for this data and can be seen in Figures 4.3 and 4.5. The MAD median result is also analysed using the MAD equation (2.3), to inspect the robustness of the points using a bar plot seen in Figures 4.4, 4.6. If a position in the mean graph has a high value, the MAD median graph tells us if the position has an outlier value. If the position has a high value in both graphs, the position overall is not even between frequencies, but if it is low in the MAD median graph, the data only have a few outliers. If a position in the mean graph has a low mean difference, it indicates a small difference between the frequencies when subtracting the sides. The results are from subject 1, B81, and 40 dB HL. The three different groups of positions are shown with different colours, the forehead is blue, the head is green, and the ear is yellow. The positions with the lowest mean values when comparing the position with each other are; the inion, temporal bone, and center forehead, seen in Figure 4.3. Two positions, Cz and ipsilateral cheekbone, have a high value compared to the other positions. The head is uneven with the inion which has a low value and Cz which has a high dB value, the same for the ear positions with unevenness.

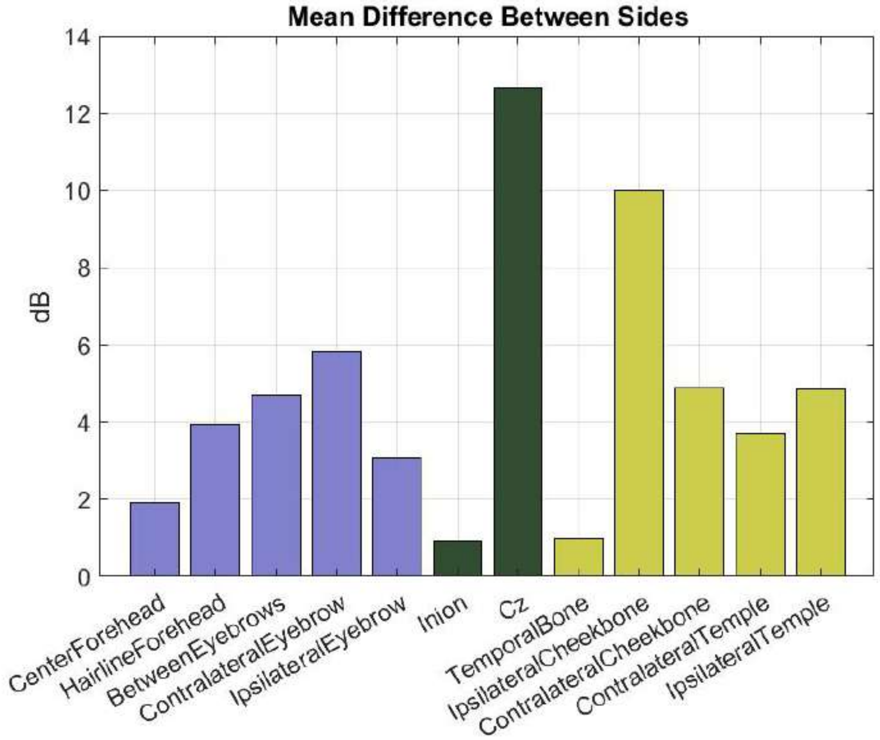

Figure 4.3: A barplot for mean value at 40 dB HL for the B81 transducer for subject 1. Inion and temporal bone show the lowest dB value, and the two positions with the highest values are Cz and ipsilateral cheekbone.

In Figure 4.4 the MAD median value is displayed, the positions are on the x-axis, and the MAD values in dB are on the y-axis. The positions with the lowest result are the temporal bone, contralateral temple, ipsilateral cheekbone, inion, and center forehead, all under 0.5 dB. However, all positions are under 4 dB. The forehead, head, and ear all have high and low values in each position group. Comparing Figure 4.3 and Figure 4.4, Cz is uneven between all frequencies because it has a high value in both graphs. Compared with the ipsilateral cheekbone, the mean value is high and the MAD median low, indicating a considerable outlier value in the data instead.

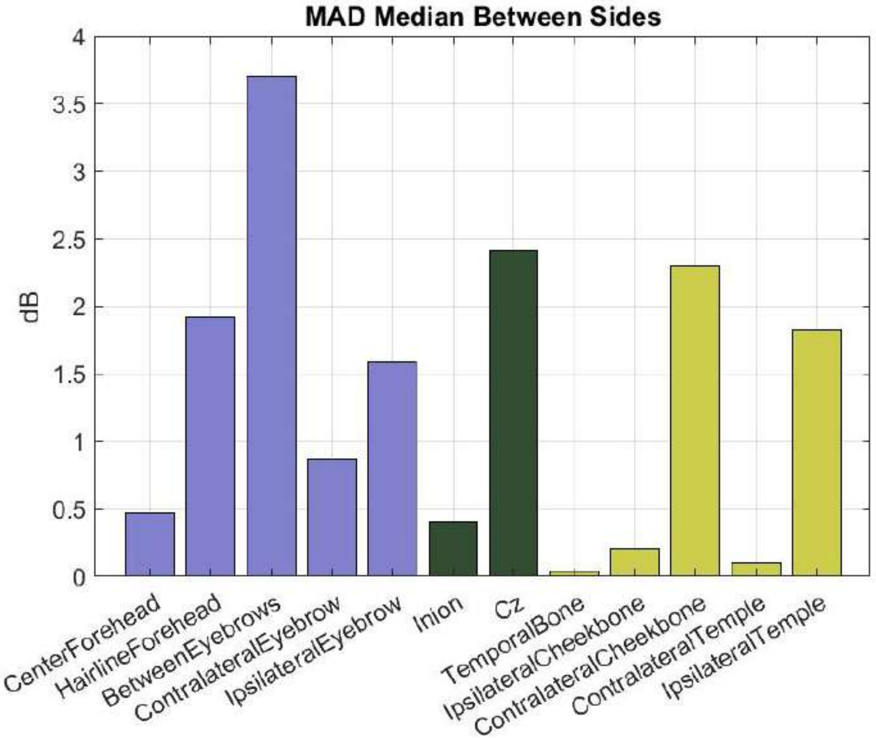

Figure 4.4: A barplot of the MAD values for 40 dB HL for each position for subject 1. The temporal bone and contralateral temple show the lowest value, and the two positions with the highest values are between eyebrows and Cz.

The last two Figures 4.5 and 4.6 show the Intenso's mean and MAD median value at 70 dB HL, for subject 1. Figure 4.5 displays the mean value, and the position ipsilateral eyebrow has one of the lowest mean values again, together with hairline forehead and center forehead. The positions around the ear with a mean over 10 dB are: contralateral cheekbone, ipsilateral cheekbone, and contralateral temple.

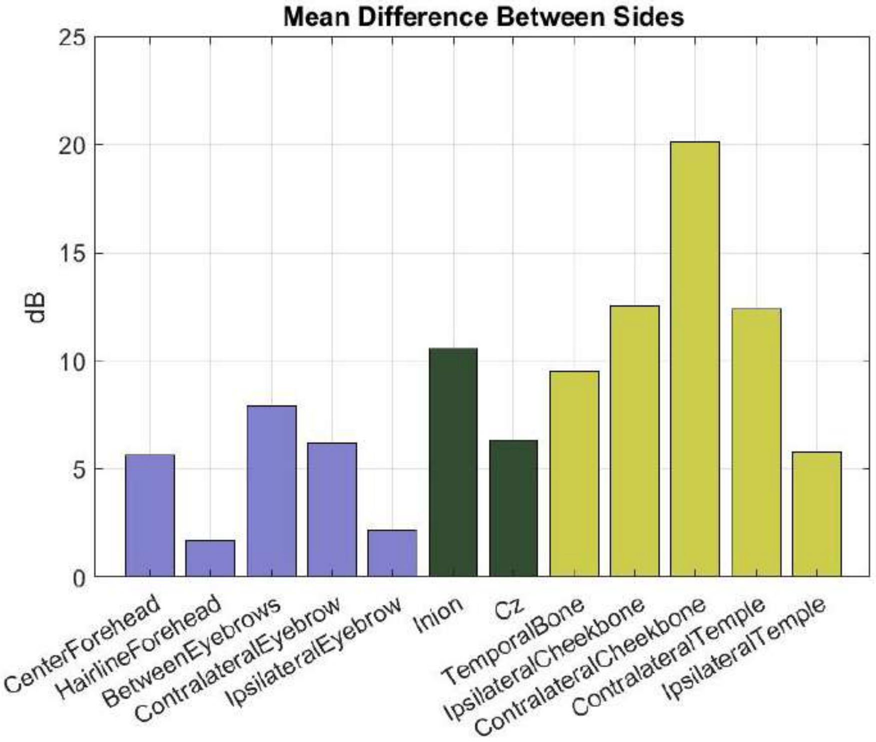

Figure 4.5: A barplot for mean value at 70 dB HL for the Intenso for subject 1. The hairline forehead and ipsilateral eyebrow show the lowest value, and the two positions with the highest values are the contralateral cheekbone and ipsilateral cheekbone.

In Figure 4.6 are the MAD values, the temporal bone, ipsilateral eyebrow, and contralateral eyebrow are the most promising positions with values under 0.5 dB. All positions are under 6 dB, but contralateral temple, ipsilateral cheekbone, and between eyebrows have the highest values. Comparing the three positions with a high mean with the MAD median graphs shows that contralateral cheekbone has a low value in the MAD median graph, indicating that the position has one considerable outlier value. The other two positions have high value in the mean and MAD median graphs revealing unevenness between the positions.

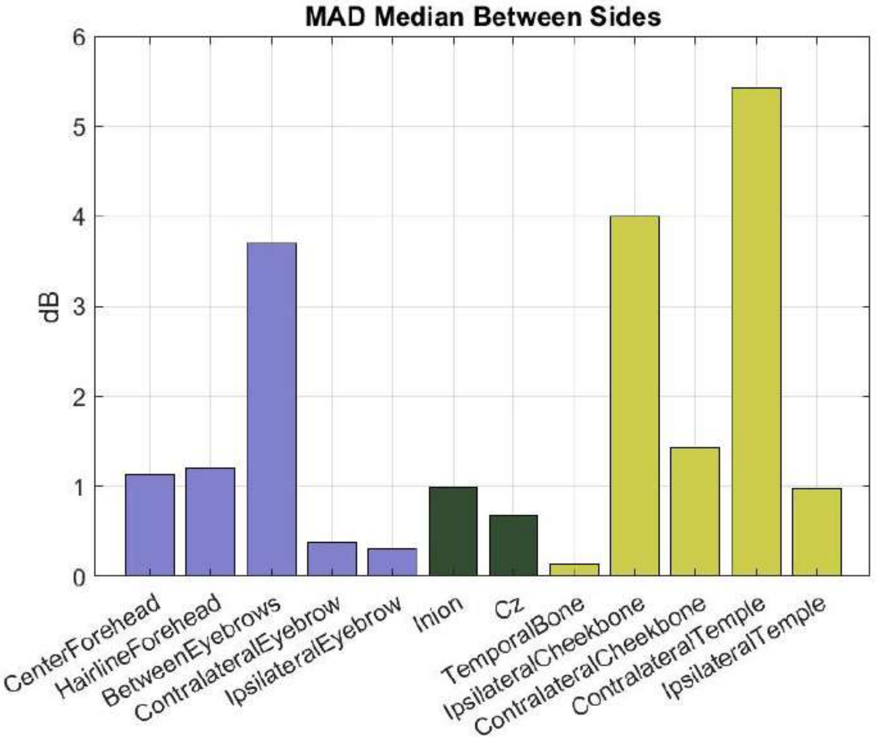

Figure 4.6: A barplot for MAD median value at 70 dB HL for the Intenso for subject 1. The temporal bone and ipsilateral eyebrow show the lowest dB value, and the two positions with the highest values are the contralateral temple and the ipsilateral cheekbone.

4.2 Trial 2

In trial 2, ten new positions are tested on the head for subject 1 and 2. Figure 4.7 shows the result for ipsilateral central and Cz, for the B81 on the left side for subject 1. The figure displays six different frequencies at 40 dB HL except for 8000 Hz at 30 dB HL, which is the case for all measurements. The result for both positions are similar, with a high dB SPL for 500 Hz and a minimum point at 2000 Hz, then increasing in value for 4000 Hz. Both positions are over the NF and are relatively even between each frequency. The value at 2000 Hz is low for many positions for the B81 for both subjects.

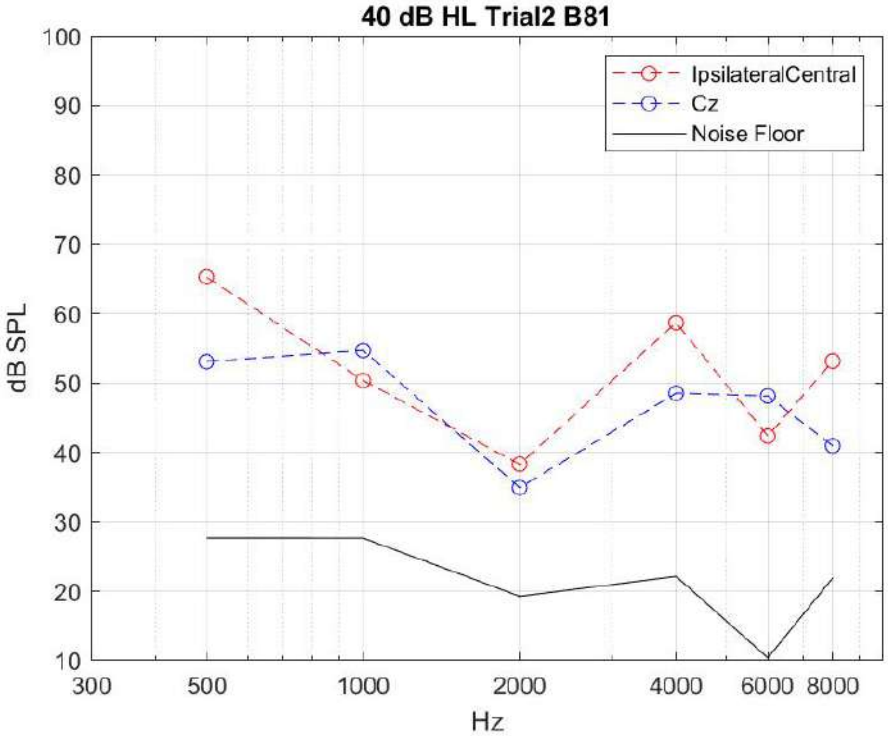

Figure 4.7: Result from B81, subject 1, 40 dB HL in dB SPL at 500, 1000, 2000, 4000, 6000 and 8000 Hz. The positions ipsilateral central and Cz are plotted together. The positions show, for some frequencies, the same characteristics.

The result from the Intenso on subject 1, using 70 dB HL except for 8000 Hz which used 50 dB HL, which is the case for all measurements, the left side is displayed in Figure 4.8 for six different frequencies. Two positions are plotted together, ipsilateral central and Cz, and the two positions have the same trend between each frequency. Both positions are increasing in value between 500-1000 Hz and 4000-6000 Hz and decreasing between 1000-2000 Hz, 2000-4000 Hz, and 6000-8000 Hz. The highest value is at 1000 Hz, and the lowest is at 8000 Hz for both positions, and all data is over the NF.

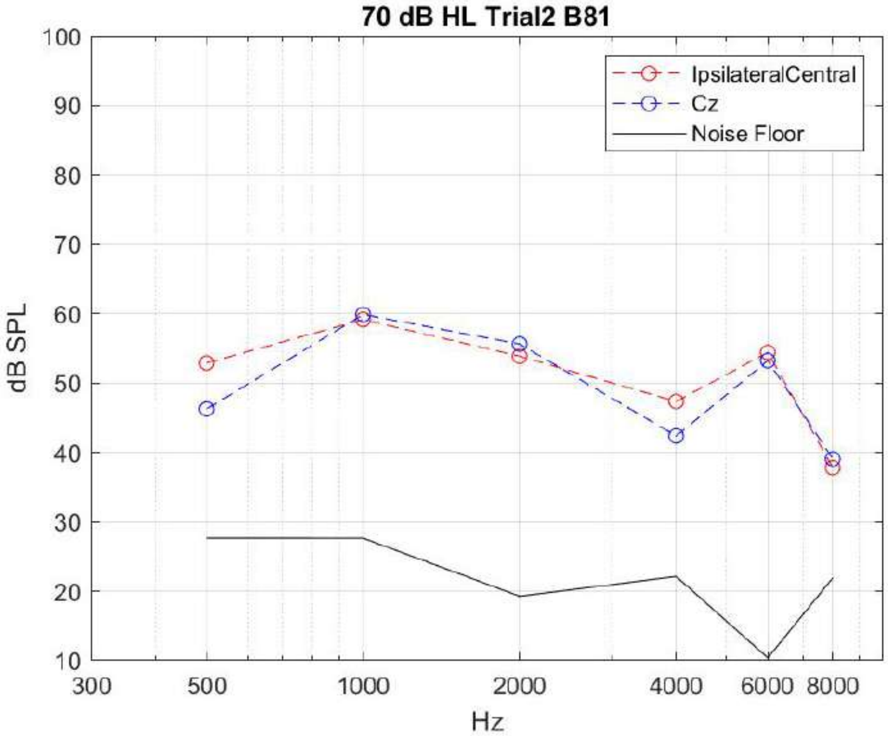

Figure 4.8: Result from Intenso, subject 1, 70 dB HL in dB SPL at 500, 1000, 2000, 4000, 6000 and 8000 Hz. The positions ipsilateral central and Cz are plotted together. The positions show the same characteristics for the six frequencies.

4.2.1 Positions from Trial 1 with Trial 2 Settings

Seven positions will be further analysed from trial 1, three from the forehead, center forehead, hairline forehead and ipsilateral eyebrow. Two positions from the ears, contralateral temple and temporal bone. Two positions from the head, the inion and Cz, but for Cz, a new measurement method is used. Therefore it will be analysed as a "new" position for trial 2. Three of the seven positions from trial 1, which is continued with, are shown in Figure 4.9 and Figure 4.10. In the first figure, the B81, subject 1 and left side are displayed. Three new frequencies are tested, 2000, 6000, and 8000 Hz, and for 2000 Hz, a decreased dB SPL value is shown. Ipsilateral eyebrow has the highest value at the higher frequencies. For the Intenso, shown in Figure 4.10, inion has the highest values for the highest frequencies and at 2000 Hz. The ipsilateral eyebrow has the lowest value at 2000 Hz, and the contralateral temple at 6000 and 8000 Hz.

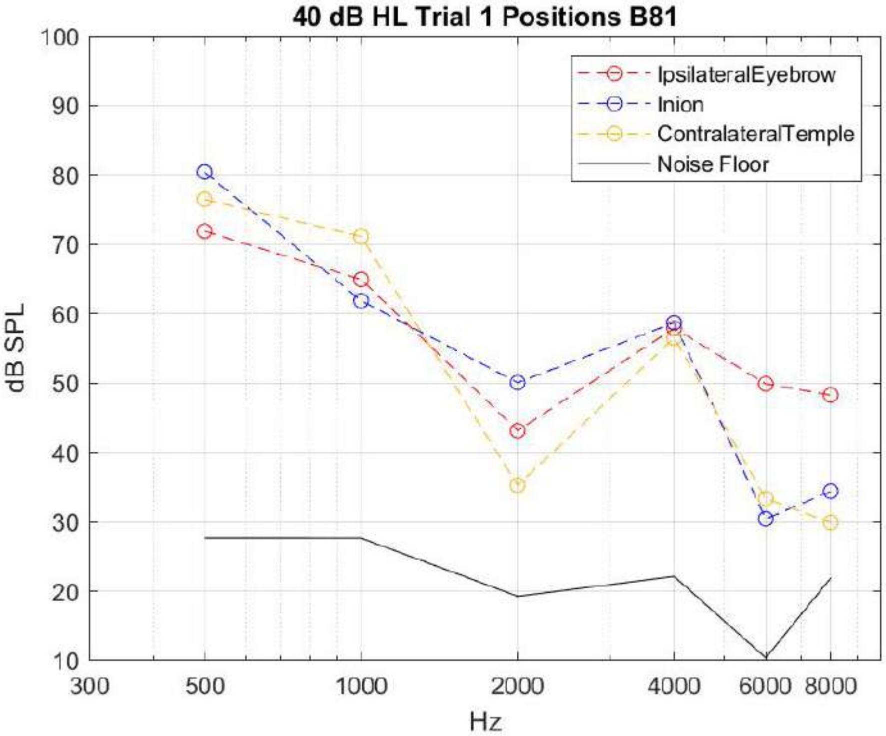

Figure 4.9: Result from the B81, subject 1, 40 dB HL, at 500, 1000, 2000, 4000, 6000 and 8000 Hz for positions from trial 1. The positions, ipsilateral eyebrow, inion and contralateral temple, are plotted. The positions show similar behaviour except for the ipsilateral eyebrow for higher frequencies that does not go down as low as the other two positions.

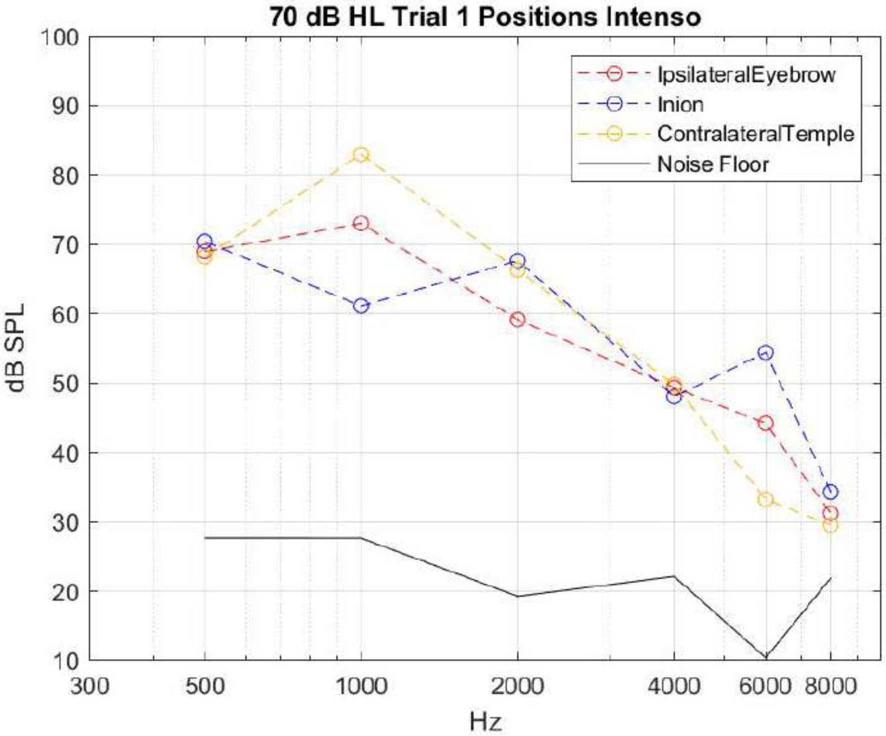

Figure 4.10: Result from Intenso, subject 1, 70 dB HL, at 500, 1000, 2000, 4000, 6000 and 8000 Hz for positions from trial 1. The positions ipsilateral eyebrow, inion and contralateral temple are plotted. The positions show similar behaviour for almost all frequencies except at 1000 and 6000 Hz.

4.2.2 Difference Between Sides

In Figures 4.11 - 4.14, the mean and MAD median of the difference between sides as explained in section 4.1.1 are shown. The positions with the red colour are from trial 1, and the light blue is the new position for trial 2 on the front of the head. The last two colours, green and yellow, are positioned on the middle and back of the head. The B81 and the Intenso are used at 40 dB HL and 70 dB HL for subject 1. In Figure 4.11, the mean value for B81 can be inspected. The three positions with the lowest values are from trial 1, temporal bone, center forehead, and ipsilateral eyebrow. Positions with higher values compared to other positions are primarily the positions on the contralateral side of the head. The MAD median for B81 can be seen in Figure 4.12, all except one position are under 5 dB. The temporal bone and center forehead have low values for the MAD median and the mean. One position, Cz, has a lower MAD median than the mean value, indicating an outlier value in the measurement.

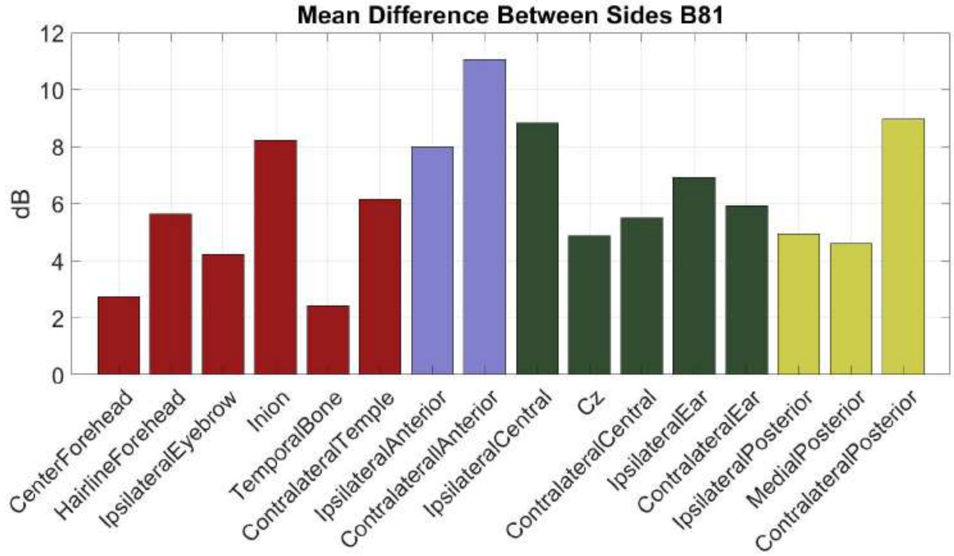

Figure 4.11: A barplot for mean value at 40 dB HL for the B81 for subject 1. The temporal bone and center forehead show the lowest value, and the two positions with the highest values are the contralateral anterior and contralateral posterior.

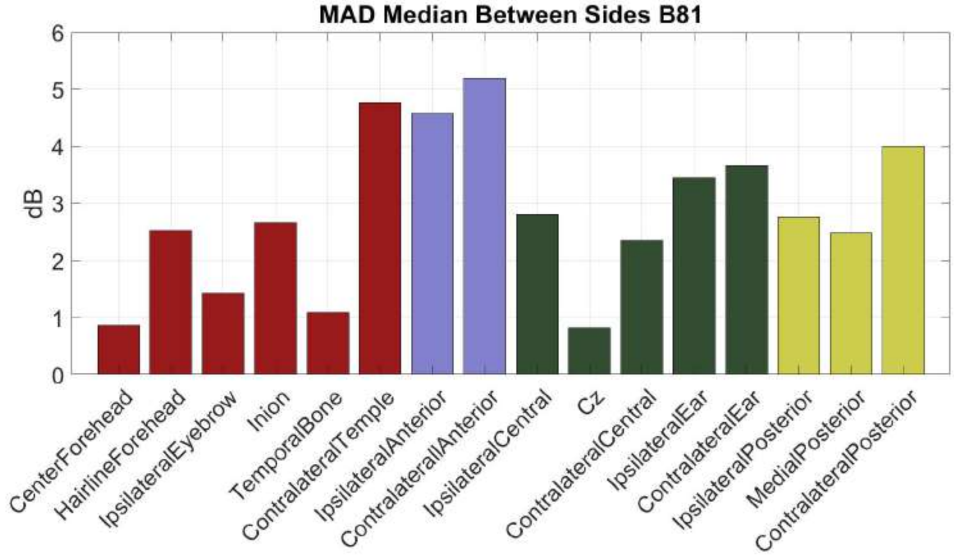

Figure 4.12: A barplot for MAD median value at 40 dB HL for the B81 for subject 1. The center forehead and Cz show the lowest value, and the two positions with the highest values are the contralateral anterior and contralateral temple.

The mean and MAD median for the Intenso are shown in Figures 4.13 and 4.14. The positions with the lowest values are the ipsilateral eyebrow, hairline forehead, and contralateral anterior. Placing the SM on the ear and contralateral temple gives the highest values. The three positions with the lowest mean also have low MAD median value compared to other positions, indicating evenness between the frequencies.

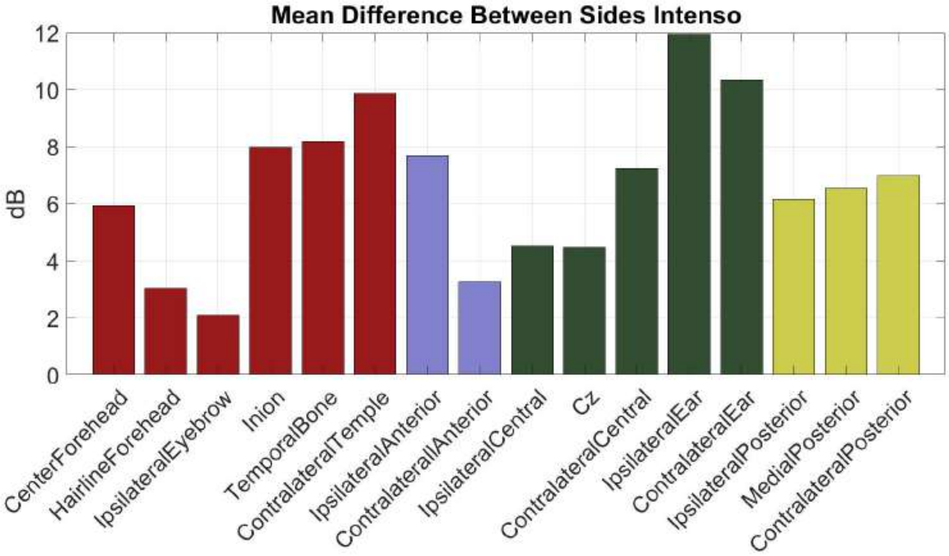

Figure 4.13: A barplot for mean value at 70 dB HL for the Intenso for subject 1. The ipsilateral eyebrow and hairline forehead show the lowest value, and the two positions with the highest values are the ipsilateral ear and contralateral ear.

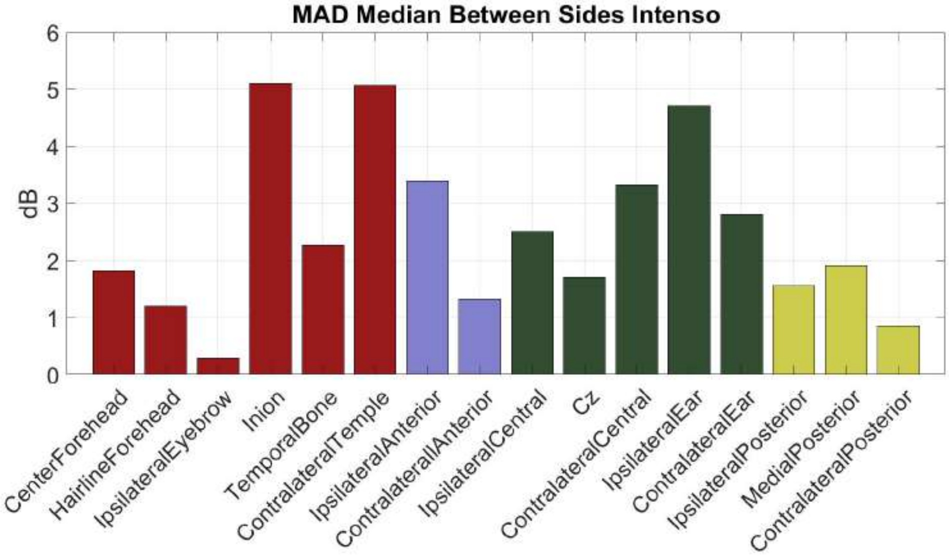

Figure 4.14: A barplot for MAD median value at 70 dB HL for the Intenso for subject 1. The ipsilateral eyebrow and contralateral posterior show the lowest value, and the two positions with the highest values are the inion and contralateral temple.

4.3 Final Measurements

Five tests are conducted in the final measurement. The input signal is at 40 and 70 dB HL, except for 8000 Hz, where the value is 30 and 50 dB HL for the B81 and the Intenso, which is the case for all measurements. All tests used six different frequencies: 500, 1000, 2000, 4000, 6000, and 8000 Hz. The first test did compare the mean and SD when each side is analysed as one measurement for the four subjects, which equals eight measurements for each device. Then a sample size test is conducted from the same data. The data from these tests is also compared when the device is on the left and right sides, investigating if there is a difference in having the device on the right or left side. The fourth test is retesting without removing the equipment, and the fifth is retesting but removing the equipment between measurements. The retests are then analysed with mean and SD. The first three tests are performed on four test subjects, and the retests only on subject 1. Seven positions are studied with the SM in the last trial.

4.3.1 Mean and Standard Deviation

The mean and SD for all subjects and all positions can be seen in Figure 4.15. Here the measurements on the left and right sides have been treated as separate measurements giving a total of eight measurements. The blue and red error plot is from the B81, respectively, the Intenso. The whole position name on the x-axis can be seen fully in the figure caption. For the B81, the means for each position are almost the same, and no difference can be seen for all positions. The SD is generally the lowest for the ipsilateral eyebrow, and Cz is the second lowest. For the other five positions, the lower frequencies have a higher SD, while the higher frequencies have a lower SD. The means between all positions for the Intenso are similar, but the SDs are lower overall than for the B81, especially for the lower frequencies. The ipsilateral eyebrow and Cz perform near the same for the Intenso as the B81, but the ipsilateral positions on the head show lower SDs for the Intenso. The B81 have a lower mean value than the Intenso at 2000 Hz for all positions, and the Intenso have a lower value for all positions at 4000 Hz and 8000 Hz. For 500 Hz, 1000 Hz, and 6000 Hz, the B81 and the Intenso have roughly similar mean values.

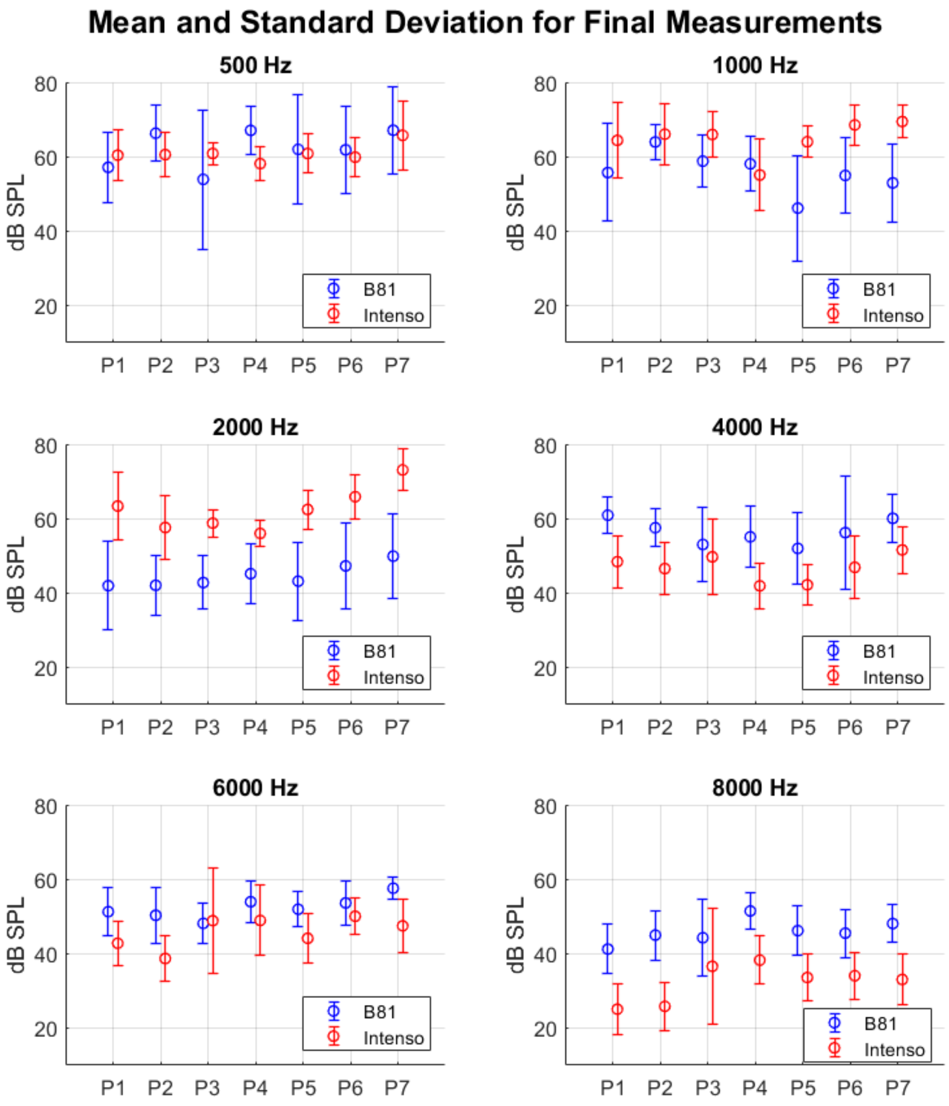

Figure 4.15: A error plot showing the mean and SD for the B81 and Intenso when each side has been analysed as one measurement for the four subjects and a total of eight measurements. Each plot represents the frequencies, 500 - 8000 Hz and the error bars represents the SD at each position for both devices.
P1=Center Forehead, P2=Ipsilateral Eyebrow, P3=Temporal Bone, P4=Cz, P5=Ipsilateral Central, P6=Ipsilateral Anterior, P7=Ipsilateral Posterior

4.3.2 Calculated Sample Size

The sample size is calculated with equation (2.4) for each position and frequency for both devices seen in tables 4.1 and 4.2. The power factor is set to 0.95, type 1 error $\alpha = 5\%$, and the sample sizes are equal. The center forehead is the position which the other positions are compared with. For the B81, two positions have four frequencies with a sample size lower than 100, the ipsilateral eyebrow and ipsilateral posterior. The ipsilateral eyebrow at 2000 Hz had a 45 times higher sample size than the second highest for the B81. At 2000 Hz, the B81 had three values over 1000 samples. Analysing the Intenso, Cz had four values under 50 samples. At 500 Hz, the Intenso have four positions with values over 1000 samples.

Table 4.1: The calculated sample size needed to receive the power equal to 0.95 and type 1 error at 5%. Two sample groups are compared, the center forehead and the position on the first column of the table. A comparison of each frequency is made and the data is for the B81

B81	500 Hz	1000 Hz	2000 Hz	4000 Hz	6000 Hz	8000 Hz
Ipsilateral Eyebrow	29	68	338666	61	1543	84
Temporal Bone	874	476	5553	44	112	304
Cz	25	817	358	52	154	13
Ipsilateral Central	244	59	2506	32	2503	50
Ipsilateral Anterior	160	7509	132	278	198	65
Ipsilateral Posterior	37	581	60	1629	29	26

Table 4.2: The calculated sample size needed to receive the power equal to 0.95 and type 1 error at 5%. Two sample groups are compared, the center forehead and the position on the first column of the table. A comparison of each frequency is made and the data is for the Intenso

Intenso	500 Hz	1000 Hz	2000 Hz	4000 Hz	6000 Hz	8000 Hz
Ipsilateral Eyebrow	49482	955	66	379	59	2139
Temporal Bone	5490	1090	104	1611	145	49
Cz	227	32	42	32	63	9
Ipsilateral Central	5931	17262	2490	35	672	19
Ipsilateral Anterior	4097	154	350	818	18	17
Ipsilateral Posterior	80	104	25	131	61	21

4.3.3 Difference Between Sides

The mean and MAD median results for the four test subjects can be seen in Figure 4.16 - 4.19, for B81 and the Intenso at 40 and 70 dB HL, for the seven test positions. The colours blue, red, yellow, and purple equal test persons one, two, three and four. In Figure 4.16 ipsilateral eyebrow has a similiar mean between the four test persons but an overall higher mean value than Cz for the B81. No patterns occur in the figure, but not more than approximately 8 dB differ from the lowest to the highest value at one position. Figure 4.17 displays the MAD median for the B81, and only two of the 28 values are over 5 dB. At position ipsilateral eyebrow for test person four and ipsilateral central, for test person one, the mean value is high and MAD median low, indicating outliers in the data.

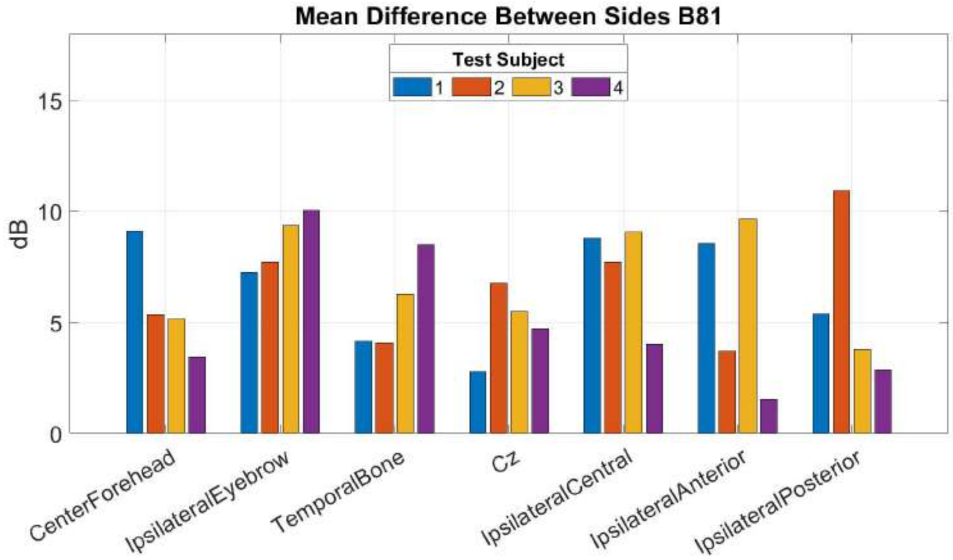

Figure 4.16: A barplot for the mean value at 40 dB HL for the B81 for the final positions for the four subjects. Ipsilateral eyebrow showed the most even result for the four subjects, but Cz and temporal bone have a lower total value between the four subjects.

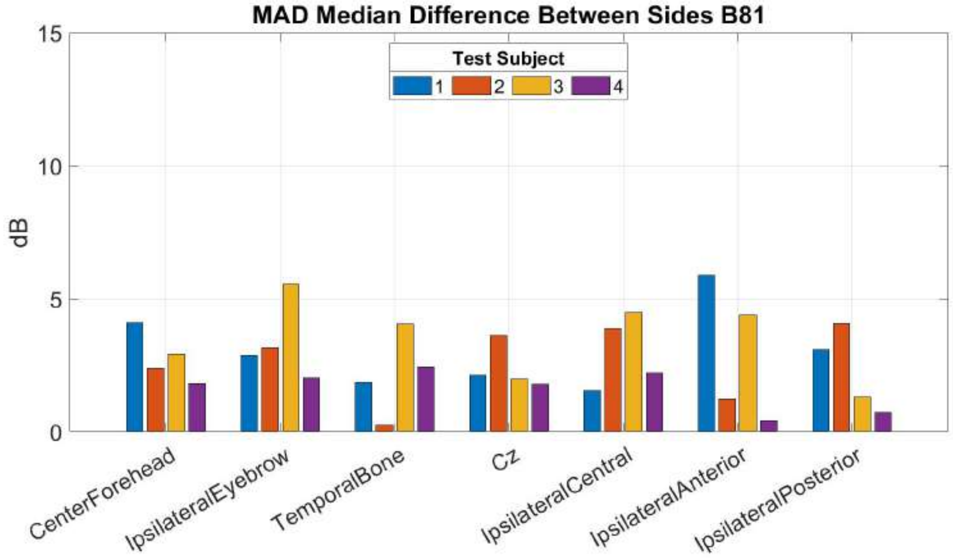

Figure 4.17: A barplot for MAD median value at 40 dB HL for the B81 for the final positions for the four subjects. All positions have a low MAD median, with only two positions with a value over 5 dB, but only for one subject.

Figure 4.18 and 4.19 display the mean and MAD median result for the Intenso for the four test subjects. Three positions, ipsilateral eyebrow, ipsilateral anterior, and Cz, have similar values for all four test subjects. Subject 3 has higher values for the positions on the center forehead and temporal bone than the other three subjects. The MAD median is shown in Figure 4.19, showing a low value for subject 3 at the center forehead, indicating an outlier value. The temporal bone has high MAD median and mean values, indicating multiple outlier values. Only two values are over 5 dB for the MAD median.

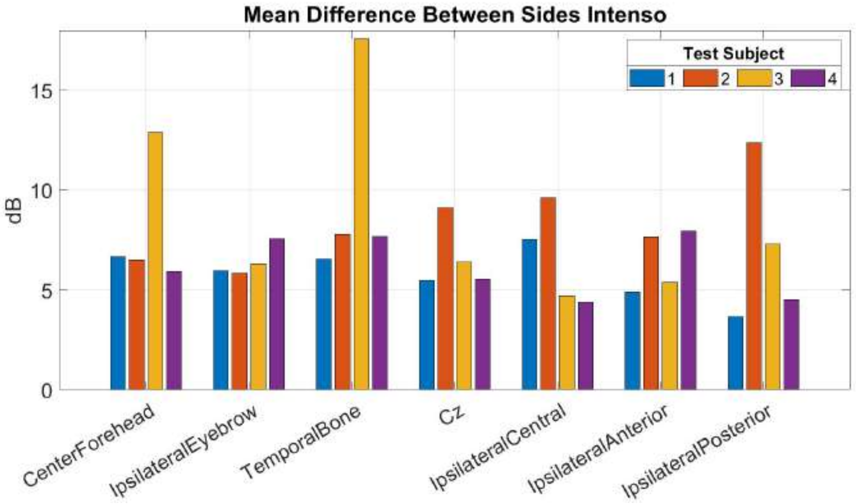

Figure 4.18: A barplot for mean value at 70 dB HL for the Intenso for the final positions for the four subjects. Ipsilateral eyebrow have the most even result between the four subjects, and most positions have similar dB values. Subject 3 has two positions with higher value and subject 2 one position.

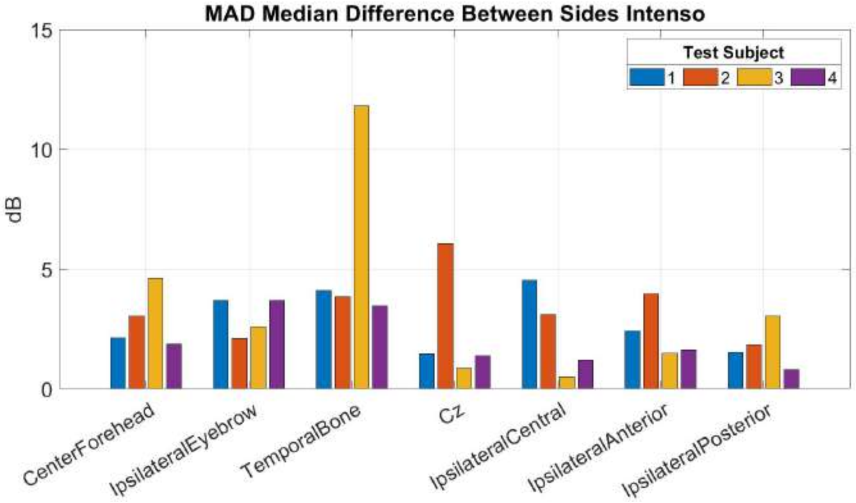

Figure 4.19: A barplot for MAD median value at 70 dB HL for the Intenso for the final positions for the four subjects. Subject 3 at temporal bone has a high value and subject 2 at Cz. The other points are lower than 5 dB.

4.3.4 Retest Without Removing the Equipment

Table 4.3 - 4.6 show the mean and SD from the repeatability measurements with subject 1 when the equipment is not removed. The measurement is done five times for each position, left and right side and six frequencies for the B81 and the Intenso. When retesting with the B81, most SDs are similar. Some values are higher than the rest, ipsilateral posterior on the left side and center forehead, ipsilateral eyebrow, Cz and ipsilateral central on the right side. For the Intenso, the SDs are also similar but overall slightly higher than for the B81 measurements. Some SDs are higher, mainly at the center forehead and temporal bone measurements on the left side and ipsilateral anterior on the right side.

Table 4.3: The mean and SD for the B81 on the left side without removing the equipment.

B81 Left	Center Forehead (dB SPL)	Ipsilateral Eyebrow (dB SPL)	Temporal Bone (dB SPL)	Cz (dB SPL)	Ipsilateral Central (dB SPL)	Ipsilateral Anterior (dB SPL)	Ipsilateral Posterior (dB SPL)
500 Hz	69.4 ± 1.6	72.3 ± 0.1	48.8 ± 7.6	65.7 ± 1.0	74.7 ± 0.6	69.8 ± 1.2	70.3 ± 5.4
1000 Hz	66.5 ± 0.6	64.9 ± 0.2	54.9 ± 0.5	63.1 ± 0.5	69.6 ± 0.8	54.5 ± 1.3	64.0 ± 3.1
2000 Hz	52.1 ± 0.9	40.8 ± 0.7	48.2 ± 4.7	50.5 ± 1.2	45.1 ± 2.8	49.9 ± 2.0	50.4 ± 3.7
4000 Hz	67.9 ± 0.2	57.0 ± 0.3	63.7 ± 0.6	56.9 ± 1.0	57.4 ± 1.2	56.7 ± 0.3	59.7 ± 0.8
6000 Hz	53.3 ± 0.4	48.7 ± 0.2	50.3 ± 0.3	44.4 ± 2.3	57.4 ± 0.4	50.8 ± 0.3	54.2 ± 0.3
8000 Hz	45.4 ± 0.8	50.3 ± 1.0	42.1 ± 1.8	50.1 ± 0.3	54.1 ± 0.1	48.1 ± 0.7	47.4 ± 0.5

Table 4.4: The mean and SD for the B81 on the right side without removing the equipment.

B81 Right	Center Forehead (dB SPL)	Ipsilateral Eyebrow (dB SPL)	Temporal Bone (dB SPL)	Cz (dB SPL)	Ipsilateral Central (dB SPL)	Ipsilateral Anterior (dB SPL)	Ipsilateral Posterior (dB SPL)
500 Hz	73.4 ± 0.6	75.2 ± 3.7	77.4 ± 0.3	65.4 ± 0.8	55.3 ± 5.8	77.7 ± 0.4	74.8 ± 0.5
1000 Hz	67.9 ± 0.6	64.7 ± 0.3	66.5 ± 0.3	46 ± 3.6	72.4 ± 0.3	63.4 ± 0.3	61.4 ± 0.2
2000 Hz	46.9 ± 0.7	43.9 ± 2.1	51.7 ± 0.6	50.8 ± 0.7	61.4 ± 0.1	60.4 ± 0.2	58.3 ± 0.2
4000 Hz	67.3 ± 0.2	51.7 ± 3.4	62.9 ± 0.3	57.6 ± 0.2	66.5 ± 0.3	68.9 ± 0.2	67.9 ± 0.1
6000 Hz	34.3 ± 2.9	49 ± 0.9	49 ± 0.5	41.4 ± 3.9	65.7 ± 0.2	57.2 ± 0.6	50.3 ± 0.5
8000 Hz	40.1 ± 1.2	47.6 ± 0.2	47.4 ± 0.4	44.6 ± 0.8	42 ± 0.5	48.9 ± 0.2	53.8 ± 0.6

Table 4.5: The mean and SD for the Intenso on the left side without removing the equipment.

Intenso Left	Center Forehead (dB SPL)	Ipsilateral Eyebrow (dB SPL)	Temporal Bone (dB SPL)	Cz (dB SPL)	Ipsilateral Central (dB SPL)	Ipsilateral Anterior (dB SPL)	Ipsilateral Posterior (dB SPL)
500 Hz	67 ± 2	69.3 ± 0.7	62.5 ± 2	53.3 ± 1.7	60.4 ± 1.4	52.7 ± 1.2	60.7 ± 5
1000 Hz	77.1 ± 3	74.2 ± 2.2	77 ± 1.9	59.4 ± 3	63.5 ± 1.8	62.4 ± 1.5	73 ± 1.5
2000 Hz	64.8 ± 10.8	65.6 ± 2.5	65.5 ± 8.8	65 ± 5.1	62.7 ± 4.5	70.2 ± 2.1	69.7 ± 3.3
4000 Hz	47.8 ± 2.9	44.4 ± 4.4	43.2 ± 6.1	43.4 ± 1.9	49.5 ± 3.1	58.2 ± 2.6	48.5 ± 2.2
6000 Hz	42.2 ± 3.7	37.5 ± 6.3	44.5 ± 3.5	56.3 ± 1.4	39.6 ± 4.1	62.3 ± 0.9	50.7 ± 2.5
8000 Hz	29.4 ± 4.6	26.8 ± 6.6	21.5 ± 2.8	31.4 ± 2.4	41 ± 1.7	52.1 ± 2.3	40.6 ± 3.1

Table 4.6: The mean and SD for the Intenso on the right side without removing the equipment.

Intenso Right	Center Forehead (dB SPL)	Ipsilateral Eyebrow (dB SPL)	Temporal Bone (dB SPL)	Cz (dB SPL)	Ipsilateral Central (dB SPL)	Ipsilateral Anterior (dB SPL)	Ipsilateral Posterior (dB SPL)
500 Hz	69.3 ± 1.0	74.8 ± 0.8	55.4 ± 2.5	60.7 ± 0.5	62.4 ± 0.9	69.4 ± 1.1	68.2 ± 2.0
1000 Hz	80.9 ± 3.3	80.6 ± 1.4	74.5 ± 2.7	68.5 ± 1.5	74.2 ± 3.0	75.8 ± 1.8	80 ± 1.2
2000 Hz	65.6 ± 4.3	59.1 ± 2.3	62.6 ± 4.1	44 ± 2.8	66.8 ± 2.8	61.9 ± 2.2	81 ± 1.7
4000 Hz	46.2 ± 3.1	41.8 ± 5.2	46.7 ± 0.8	43.7 ± 2.4	44.8 ± 4.3	44.6 ± 7.8	56 ± 4.5
6000 Hz	46.8 ± 3.8	44.1 ± 4.8	53 ± 1.7	59 ± 1.3	40.5 ± 4.5	38 ± 7.5	45.5 ± 3.3
8000 Hz	31.5 ± 2.3	28.3 ± 4.3	42.6 ± 1.8	33.5 ± 3.4	41.4 ± 2.2	25.1 ± 1.3	27.9 ± 2.5

4.3.5 Retest when Removing the Equipment

The mean and SD when removing the equipment are shown in Table 4.7 - 4.10. The measurement is done five times for each position, left and right side, and six frequencies for the B81 and the Intenso. The SDs between the B81 and Intenso are more similar, while they are not as low as for Tables 4.3 - 4.6. Some SDs are as high as 18 dB SPL, and many are over 10 dB SPL. There are still no differences between the left and right side measurements.

Table 4.7: The mean and SD for the B81 on the left side when the equipment is removed.

B81 Left	Center Forehead (dB SPL)	Ipsilateral Eyebrow (dB SPL)	Temporal Bone (dB SPL)	Cz (dB SPL)	Ipsilateral Central (dB SPL)	Ipsilateral Anterior (dB SPL)	Ipsilateral Posterior (dB SPL)
500 Hz	64.1 ± 2.7	73.9 ± 2.2	65.3 ± 10	71.6 ± 5.3	67.3 ± 7.3	70.1 ± 4.8	69.8 ± 3.4
1000 Hz	65.4 ± 0.8	65.1 ± 1.4	60.1 ± 5.5	59.5 ± 11	51.3 ± 6.7	55.2 ± 3.1	62 ± 2.5
2000 Hz	49.4 ± 2.8	43.5 ± 2.9	46.1 ± 3.4	43.2 ± 8.9	44.3 ± 6.8	48.5 ± 6.5	54.2 ± 0.8
4000 Hz	59.3 ± 13	57.4 ± 5.0	60.9 ± 3.2	58.5 ± 2.8	58.1 ± 1.1	58.8 ± 9.2	63.3 ± 1.5
6000 Hz	53.8 ± 2.5	46.1 ± 3.6	45.9 ± 5.9	53.3 ± 4.2	51.4 ± 8.9	54.8 ± 3.2	57.7 ± 2.3
8000 Hz	38.5 ± 4.5	39.7 ± 4.7	38.9 ± 3.7	48.7 ± 7.0	48.2 ± 6.9	50.3 ± 4.8	48.5 ± 3.2

Table 4.8: The mean and SD for the B81 on the right side when the equipment is removed.

B81 Right	Center Forehead (dB SPL)	Ipsilateral Eyebrow (dB SPL)	Temporal Bone (dB SPL)	Cz (dB SPL)	Ipsilateral Central (dB SPL)	Ipsilateral Anterior (dB SPL)	Ipsilateral Posterior (dB SPL)
500 Hz	62.4 ± 6.5	67.7 ± 8.6	71.5 ± 3.3	67.7 ± 6.9	63.3 ± 15	64.8 ± 7.3	69.9 ± 3.5
1000 Hz	67.5 ± 2.5	65.5 ± 2.8	63.6 ± 2.1	58.1 ± 3.5	56.4 ± 11	58.4 ± 2.4	66.2 ± 4.6
2000 Hz	48.4 ± 2.3	42.7 ± 3.0	49.5 ± 3.0	42.2 ± 5.5	40.3 ± 4.6	48.2 ± 8.4	57.9 ± 1.6
4000 Hz	64.2 ± 6.4	61.9 ± 6.3	58.9 ± 1.8	56.6 ± 3.5	58 ± 3.1	63.3 ± 6.5	53.6 ± 12.1
6000 Hz	50.9 ± 7.1	50.7 ± 5.0	43.6 ± 4.4	50.7 ± 2.9	54.4 ± 8.0	58 ± 3.6	55.7 ± 6.0
8000 Hz	42.8 ± 5.5	44.2 ± 2.1	39.4 ± 4.4	48 ± 6.5	46.3 ± 5.5	43.9 ± 12	44.4 ± 4.3

Table 4.9: The mean and SD for the Intenso on the left side when the equipment is removed.

Intenso Left	Center Forehead (dB SPL)	Ipsilateral Eyebrow (dB SPL)	Temporal Bone (dB SPL)	Cz (dB SPL)	Ipsilateral Central (dB SPL)	Ipsilateral Anterior (dB SPL)	Ipsilateral Posterior (dB SPL)
500 Hz	63.8 ± 2.9	70 ± 5.3	58.6 ± 5.1	55.7 ± 2.1	56.7 ± 2.9	60.6 ± 5.6	63.4 ± 2.9
1000 Hz	72.2 ± 4.6	73.2 ± 1.7	75.4 ± 6.0	59.5 ± 5.9	59 ± 4.2	69.3 ± 6.7	73.1 ± 9.1
2000 Hz	67.5 ± 8.9	60.9 ± 7.0	55.8 ± 9.3	52.2 ± 14.1	60.6 ± 5.8	65.4 ± 7.1	74.5 ± 8.2
4000 Hz	49.4 ± 7.0	46.2 ± 5.1	39.9 ± 10	40.9 ± 4.3	46.3 ± 0.3	46.5 ± 1.9	48.8 ± 4.5
6000 Hz	49.3 ± 13	40.3 ± 7.2	43.1 ± 10	55.5 ± 1.7	50.2 ± 11	54 ± 6.3	51.3 ± 7.7
8000 Hz	27.1 ± 7.2	26.6 ± 5.4	29.5 ± 9.2	36.9 ± 4.4	41.8 ± 7.2	38.7 ± 8.7	39.9 ± 4.3

Table 4.10: The mean and SD for the Intenso on the right side when the equipment is removed.

Intenso Right	Center Forehead (dB SPL)	Ipsilateral Eyebrow (dB SPL)	Temporal Bone (dB SPL)	Cz (dB SPL)	Ipsilateral Central (dB SPL)	Ipsilateral Anterior (dB SPL)	Ipsilateral Posterior (dB SPL)
500 Hz	64.6 ± 2.1	70.5 ± 4.1	54.9 ± 14	57.6 ± 4.3	57.7 ± 4.2	64.4 ± 3.7	68.2 ± 9.1
1000 Hz	75 ± 2.9	68.6 ± 13	71.1 ± 3.9	62.8 ± 4.9	62.5 ± 5.4	66.9 ± 3.5	72.5 ± 14
2000 Hz	68.1 ± 7.3	64.7 ± 3.3	65.6 ± 5.7	57 ± 6.6	62.7 ± 2.6	66.9 ± 7.8	74.6 ± 5.0
4000 Hz	45 ± 3.4	44.8 ± 10	41.8 ± 12	42.8 ± 6.5	40.3 ± 3.8	48.7 ± 7.3	54.5 ± 8.0
6000 Hz	44.3 ± 4.5	41.4 ± 16	49.2 ± 7.2	51.4 ± 3.9	50.6 ± 7.3	52.4 ± 6.3	46 ± 8.7
8000 Hz	28.9 ± 6.7	29.9 ± 18	29.8 ± 14	35.2 ± 7.4	37.8 ± 7.0	41 ± 3.6	36.2 ± 9.3

5

Discussion

By trying to determine where to find the most accurate position to measure BC sound induced in the skull from a BCD with a SM, many decisions have been made throughout the study. These decisions and results will be motivated and discussed in this next chapter. It will be divided into five different parts where the first part was where the more general findings were discussed and motivated. While the other four parts were trial 1, trial 2, final measurements and future research related findings.

5.1 Measurement Settings

At the start of the study, the SM was used with a softband to keep it in place. When placing the earmuff over the SM, it was problematic to know if it was still in the same place it was initially placed in, which could impact the measurements. There was also no control over how much pressure the SM was applied with, and there were indications that this could affect how well the signal was measured. The earmuff did not seal around the SM on all positions, making it more prone to pick up air-conducted sound. This was especially true for the positions over the eyebrows and between eyebrows because of the shape of the head. The leakage was a more prominent factor when measuring with the Intenso as the speakers send out the tone, which was not the case for the B81. If the SM picks up the air-conducted sound, it no longer only measures the sound induced by the Intenso or the B81. This could be a problem as the SM does not measure what it was intended to measure. A study on how much the leakage affects would be desired as it was a big part of these measurements

When calibrating the SM, a sweep from 100 to 10000 Hz was done using the Agilent signal analyzer. Due to the resolution of the sweep, the exact frequencies of interest could not be used; instead, the closest frequency was used. The resolution differ 0-25 Hz. The impact of this on the result was negligible because checking the nearby frequencies, the difference in dB was minimal. It would be desired that the signal analyzer shows results on the exact same frequencies as used from the audiometer, but as mentioned, the impact was minimal.

Two different devices were chosen for this study, one was more used in clinical settings, the B81, and one regular skin-drive BCD, the Intenso. Both devices were of interest because of the difference between them. For the B81 transducer, the input signal could be sent directly from the audiometer, which decreases the chance of an incorrect output signal from the BCD, which was more user friendly clinically. The Intenso input signal was not sent directly into the device. Instead, a loudspeaker sends out the signal, and the microphone on the Intenso receives the signal and thereafter sends the signal into the skull bone. It makes it more complicated to use but instead gives an understanding of the result in a real life scenario. The saturated level for both devices was never breached during the study, and the saturated levels for the B81 and the Intenso can be found in sections 2.5.1 and 3.2.1.

Both devices use the skin-drive technique, which has a more challenging time sending signals at higher frequencies because of the skin, mentioned in section 2.5. A limitation of the study was that only the skin drive devices were analysed, which can negatively affect the result for the higher frequencies. In a future study using direct-drive devices, the result for higher frequencies could have higher values than in this study.

The sound induced into the skull bone by either the B81 or the Intenso will not go straight to the SM. The bone-conducted sound could be amplified or reduced in the skull bone after entering from a BCD and also be weakened by the skin, which has been proven for skin-drive devices for higher frequencies mentioned in section 2.5. The input dB HL was not converted into the resulting dB SPL and not compared in this study for these reasons.

The devices used different attachment methods, and the B81 used a steel spring headband which applied more pressure than the softband on the Intenso, which could affect the result. The Intenso also had feedback and ringing problems for lower frequencies. However, the decision to keep the input signal was made because the signal was below the saturation level and above the NF.

Few data points were used for each SD measurement; more would have been beneficial, and the normal distribution was inaccurate because of the few points and, therefore, give a somewhat misleading SD. However, because of the limitation of the amount of test subjects and that SD was more commonly used than, for example, MAD median, SD was chosen for most of the measurements. However, When new positions were tested, the MAD median was chosen instead of the SD for data analysis because the data for some positions had outliers, and the MAD median method was not affected in the same way as SD for outliers.

Two earlier studies have been done with the SM (Hodgetts et al, 2018; Persson et al, 2022) mentioned in section 2.6.1. However, these studies did not focus on finding the best placement on the head for the SM, but on using the SM as a verification method for BCD, and objective measurements. Therefore, what could be of more importance when analysing the result was unknown. In an early stage, speaking tests and frequency sweep as input signal was terminated because the output signal was difficult to analyse and use in a clinical setting, where repeatability was vital. Therefore, a tone signal as input and a frequency sweep was used to analyse the tone signal because of the repeatability possibility. Thereafter, two decisions were made. The first one to look more specifically at the BCD on the right and left side should yield the same result because patients could have the device on either ear. The second decision was that the dB SPL should be similar over frequency; thus, the signal from the BCD to the SM was not amplified or vice versa, leading to a more straightforward use in clinical settings because the dB SPL should be the same for all frequencies. The first method used the mean and MAD median methods. Taking the difference between the right and left side and a low mean value indicating a slight difference between the frequencies and MAD median, implying if the data had outliers. The evenness between frequencies was examined by visually investigating the raw data plots.

5.2 Trial 1

In the first trial, three frequencies were chosen as a starting point. These frequencies were 500, 1000 and 4000 Hz to cover one, low, mid, and high frequency while keeping the number of frequencies low. For the choice of dB HL levels, it was essential to not be below the NF while not exceeding the MPO of the B81 and Intenso. The dB HL level for B81 was chosen to be 30 and 40 dB HL. The two levels were chosen because it was sought to test if there was a dependency between higher and lower dB HL levels. Values below 30 dB HL were close to the NF, and over 40 dB HL was uncomfortable for the user and close to the saturated level. Only one dB HL level was tested on the Intenso, the case for this was that values under 70 dB HL were close to or below the NF, and values over 70 dB HL were close to the saturated level. Therefore the dependency between the dB HL levels for the Intenso was not analysed.

In earlier studies with the SM, it has only been placed in the center of the forehead. This position was kept and used as a starting value. Four other positions were then added to the forehead. These were placed on the hairline straight above the center, between the eyebrows straight below the center, above the left eyebrow straight above the left eye and above the right eyebrow straight above the right eye. The reason for choosing the four new positions on the forehead was to see if any positions gave a better result than placing it in the center of the forehead. The four new positions were symmetrical outlied to cover as much of the forehead as possible in the measurements.

Two other areas were of interest to test, around the ear and on the head. The positions around the ear used landmark points to identify the position. The landmarks points were the temple, cheekbone and temporal bone behind the ear, where the BCD usually was placed. The temple and cheekbone positions were measured on the ipsilateral and contralateral sides of the B81 and the Intenso. In contrast, the position on the temporal bone was only measured on the contralateral side. The positions around the ear were chosen because they usually do not have hair covering the skin. The last area that was explored was the two positions on the head. These were right in the center of the scalp (Cz) and the back of the head on the inion. The choice for these positions was to see the effect of having hair between the SM and the skin.

Measuring the B81 with two different dB HL levels to test if there was a dependency between the dB HL levels. It was seen that there was a stable offset between the 30 dB HL and 40 dB HL measurements which can be seen in Figure 4.1. The offset varied from 9 to 10 dB, and the behaviour was similar for all frequencies. The data from this signify that as long as the measurement was done at a dB HL value high enough to breach the NF while not maxing out the B81 or Intenso, it will have similar behaviour but with an offset in dB. It would be beneficial to confirm this with the Intenso as well, but as the interval from where the NF was breached to where the Intenso was saturated was very narrow, this was not possible. Nevertheless, there were indications during testing that the Intenso had the same behaviour.

Comparing the measurements from the B81 in Figure 4.1 with the ones from the Intenso in Figure 4.2, there was no similarity between most positions. However, when comparing the devices' positions separately, most positions behave similarly. The inion stands out from the others in Figure 4.2 for the Intenso, while there was similar behaviour across all positions in Figure 4.1 for the B81. The cause for the difference between the devices was probably that the devices were being stimulated differently. A second reason could be the difference between the steel band for the B81 and the softband for the Intenso, as the steel band applies much more pressure on the B81 and the skin. The problem comes down to the limitation of using skin-drive devices in this study and not trying direct-drive devices and see how these devices were affected as well.

The data without any modifications was studied, but overall, the data shows the same characteristic. Therefore, no positions were removed or added to the next trial from analysing the raw data. Instead, the different positions were evaluated by emphasising the positions behaving similarly regardless of having the B81 or Intenso behind the right or left ear. Comparing this, the mean difference between the sides was calculated, and the MAD median across the three frequencies for all positions was investigated. These values were visualised in Figure 4.3 and Figure 4.4 for the B81 and in Figure 4.5 and Figure 4.6 for the Intenso.

The positions kept for trial 2 from trial 1 were the hairline on the forehead and the ipsilateral eyebrow. These positions had, for the most part, better mean compared to other positions and MAD median values on both the Intenso and the B81 for both subjects in trial 1. Positions such as the contralateral temple and temporal bone were kept because they were good on one device or one subject but showed poor results on the second device or second subject. Both positions on the head were kept because they were used in trial 1 mostly to see how the hair affected the measurements and showed good compelling results, which will be investigated further in trial 2. The last position, the center of the forehead, was kept as it showed decent results in trial 1 for subject 1 but was kept in all trials because it was used in two earlier studies by Hodgett et al. (2018) [19] and Persson et al. (2022) [16]. After analysing the trial 1 results, it can be seen that more frequencies need to be tested to see if the frequency range impacts the result differently at specific frequencies. This could not be seen with only three frequencies tested in trial 1.

5.3 Trial 2

In trial 2, only one dB HL level was tested for each device, and this was because a change in the dB HL level only gave the data an offset, as seen in trial 1. Three new frequencies were added to the measurements because, from trial 1, it was seen that higher frequencies could be of interest. Since the pure tone audiometry was in the range of 250-8000 Hz and the SM was developed for clinical use, it would be interesting to see results from higher frequencies. The Intenso could also handle higher frequencies better with less feedback problems. The dB HL level for the Intenso was 70 dB HL because it was over the NF and below the saturated level. However, because of limitations in the audiometer, at 8000 Hz, a maximum of 58 dB HL can be outputted, and for simplicity reasons, 50 dB HL was chosen. The B81 also had one constraint at 8000 Hz, 30 dB HL was outputted instead of 40 dB HL because the subjects felt an uncomfortable at 40 dB HL.

Ten new positions, eight on the head and one on each ear, were investigated in trial 2. The motivation for this was that in trial 1, both Cz and the inion showed promising results, and the hair did not affect the SM. The eight positions on the head were symmetrically chosen, two at the anterior level, three at the central level and two on the posterior level of the head. The 10-20 method was used to calculate the positions, with the help of percentages from known landmarks on the head. This was because humans have different-sized heads, and using percentages, the placement of the positions will be more similar between subjects. The position of Cz, was remeasured with the 10-20 method, to get a more accurate reading on the head in trial 2. In trial 1 the placement method was just to place it on the top of the head. Therefore in the result, Cz was in the same group as the new position from trial 2. Only two new positions were tested on the anterior of the head, one to the left (F3) and one to the right (F4) and no new in the middle. The argument for not including a positions in the middle was that it was too close to the hairline position.

In trial 1, a problem with measuring the Cz and inion position was discovered. The headband was challenging to use comfortably for positions on the head, and the pressure from the headband onto the head differed between positions. Therefore a new attaching arrangement was built with a softband, for more details, see section 3.3.1. The new attaching arrangement was used for all measurements in trial 2 and in the final trial to get similar conditions in each test.

The results from trial 2 show similar characteristics for the positions for both the B81 and Intenso. At 2000 Hz for the B81, the measurement values decrease for most positions for subjects 1 and 2, seen for subject 1 in Figures 4.7 and 4.9. The cause for this could be some limitation in the B81 design. The values from the Intenso were more even overall for subjects 1 and 2, seen for subject 1 in Figures 4.8 and 4.10. All positions in trial 2 show similar characteristics in the raw measurements plot. Therefore no positions were removed in this analysing step. However, the positions differ when examining the difference between the right and left sides.

When selecting positions for the last measurement, two positions from the forehead, one around the ear and four from trial 2 were chosen. The center of the forehead was selected for the final measurement directly because the position was used in two earlier studies by Hodgett et al. (2018) [19] and Persson et al. (2022) [16]. For subject 1, the ipsilateral eyebrow and temporal bone had one of the lowest mean value for the B81, and subject 2, had low mean values for these positions but with the Intenso instead. These two positions were selected for the final measurement. The positions on the ipsilateral and contralateral sides on the head had promising results. Here both sides could be continued with, but as they were similar, only one side, ipsilateral, was chosen for the final measurements. Also, no relationship was found between the positions on the anterior and posterior sides. Therefore, the ipsilateral side was kept to continue to investigate this factor. The last position picked was Cz, which had a low dB mean value for both subjects for the Intenso device compared to the other positions, seen in Figure 4.13 for subject 1. Subject 1 felt discomfort during the measurement of the ipsilateral and contralateral ear, and this was one reason it was excluded in the final measurement, together with high mean values.

5.4 Final Measurements

In the final measurements, four subjects and seven positions were tested with the same method as in trial 2. All measurements were done the same week and one time, except for subject 3 for the B81 measurements. The test was performed again because the result was 20-30 dB SPL lower than for the other three test subjects and below the NF. It was later found that it was a faulty wire between the SM and Agilent. The measurement with the new wire was closer to the other subjects'. The positions with the lowest SD, when each side counted as one measurement, were the ipsilateral eyebrow for the B81 and the ipsilateral positions on the head for the Intenso seen in Figure 4.15. The B81 had mean values close to 40 dB SPL at 2000 Hz and 8000 Hz, which was lower than the other frequencies. At 8000 Hz, the input signal was lower, which could explain this behaviour. Nevertheless, at 2000 Hz, the B81 seems to have difficulties. At first sight, this could be because the skin suppresses high frequencies, but the mean value at 4000 Hz and 6000 Hz was around 50 dB SPL. One reason could be that the B81 have some problem at 2000 Hz. As mentioned earlier in the discussion, the Intenso had feedback/ringing issues for lower frequencies. This behaviour did not impact the SD in the final measurements according to Figure 4.15 as the SDs were similar across all frequencies. It could be that it affects the measurements, and the SDs for the lower frequencies should be smaller.

The sample size calculations seen in tables 4.1 and 4.2 indicate how many measurements were needed for a significant result if the power equals 0.95 and type 1 error $\alpha = 5\%$. For both devices, the ipsilateral posterior shows promising results with overall lowest values, and for the Intenso, the highest value was at 131 samples, which was acceptable. Important to consider was that only eight measurements were used to calculate the approximate sample size needed. If the data contains one outlier value at a specific position and frequency, the sample size can be affected drastically. The decision to compare the positions with the center forehead was that this position has been used in earlier studies, and investigating this to find a more suitable placement for the SM compared to the center forehead seemed reasonable. Performing the measurements for around 30 samples for the most promising positions seems suitable for future research and investigating the significant data level of the data. The reason for around 30 samples was that when the sample size was small, one could argue that the outlier values affect the data. Therefore 30 samples were chosen because the lowest values were around this value for multiple positions and frequencies.

Figures 4.16 and 4.18 show the mean difference between the right and left sides. For the B81, the ipsilateral eyebrow had an even result for all four subjects, but the dB was higher than other positions. The position Cz has a low value for all subjects but not as even as the ipsilateral eyebrow. For the Intenso, the ipsilateral eyebrow had one of the lowest values for all subjects and the most even. Two other positions, Cz and ipsilateral anterior, also have low and even values. Looking at the raw data, subject 3 for the B81 left side, the ipsilateral eyebrow, the result was below the NF, but similar to the other subjects at the other frequencies. The cause for this could be an error or a human factor under the testing. It should also be mentioned that when comparing the highest and lowest mean difference for a position between the subjects the difference was the highest at approximately 8 dB for the B81 at the ipsilateral posterior and approximately 10 dB for the Intenso at the temporal bone. This could be compared with the ipsilateral eyebrow where the difference was approximately 3 dB and 1.7 dB for the B81 and the Intenso. A few measurements at 8000 Hz were below the NF, but essential to consider was the lower input dB HL sent at this frequency for both devices. Besides these two factors, the raw data for the four subjects does not stand out and were similar between the subjects. Subject 3 had difficulties setting up the ipsilateral central position and needed to hold the softband for the attaching arrangement to keep everything in position. The three other subjects did not have the same problem.

Retesting the measurements without removing and removing the equipment was done five times for each measurement, but only on subject 1. Ideally, this would be done on all four subjects, but as time was a factor here, it was difficult to do this without booking the subjects for multiple days. The results showed in Table 4.3 - 4.10, the SD were similar across most frequencies and positions. The SDs for the Intenso measurements were higher overall, but this was not surprising due to the air conducted sound leakage from the loudspeaker and the ringing/feedback issues. When removing the equipment between measurements, the SDs increased slightly. The difference between the B81 and Intenso was also smaller, as this increased the SDs more for the B81 than the Intenso. The increased value when removing the equipment between measurements was most probably due to the exact placement of the SM as well as how tight the SM was to the skin. Ipsilateral eyebrow had for the right side Intenso high values for most frequencies seen in Table 4.10, but not for the left side or B81 to the same extent. The high values could be because the position was worse than other positions. However, it could occur due to human factors placing the SM incorrectly, or the pressure the SM was applied with was different.

When analysing the result, it was essential to consider if the leakage from the earmuff affects the ipsilateral eyebrow position. However, the position was promising for both devices, and the leakage affecting the B81 result was most likely minimal because the test room was silent under the B81 measurements and the AC noise from the transducer was also minimal. Nevertheless, the results from the Intenso could be affected negatively and need to be investigated further.

5.5 Future Work

This study has several areas that would need more in-depth research:

- Due to the limited research, it would be beneficial to study how much a bone-conducted sound was amplified or reduced in the skull bone after entering from a BCD. If this was done, it could be easier to distinguish between the positions and whether they were more suitable.
- How the pressure on the SM affects the result. At the start of this study, it was found that if the SM were to loose, the SM would get no signal. It would be interesting to investigate if the signal changes for higher pressure. The same argument, but for the pressure for the B81 and the Intenso, could be used if the dissimilarity in result occurred because of the different pressures onto the head.
- Another interesting future research topic was how much pressure the earmuff should be applied to the head and if the pressure of the earmuff affects the result.
- Doing the measurements with direct-drive devices and the implanted skin-drive device to investigate if these devices give similar results as transferring the signal via the skin as was done in this study.
- A study on how much the earmuff helps against leakage from the loudspeaker,

whether the sound from the loudspeaker was loud enough to penetrate through the earmuff to the SM, and if an alternative method needs to be developed for sound leakage, especially for positions that have some leakage, like the eyebrows.

- The last topic that would benefit from future work was doing the retests on multiple subjects, as there only was time to do these on one of the subjects in this study. This would also help to see behaviours and dependencies on the different positions and frequencies.

6

Conclusion

The aim of this study was to find the optimal position of the SM to measure bone conducted sound induced in the skull. This was done by either using a B81 transducer or an Intenso hearing aid together with a SM based on an electric condenser microphone from Sonion. Tones at specific frequencies and levels were applied from an audiometer. The measurements were made on six frequencies ranging from 500 to 8000 Hz for the simplicity of redoing the measurements in a clinical environment and getting a general view of how the bone conducted sound behaves in the hearing interval. The most optimal position was the ipsilateral eyebrow when analysing the evenness between the left and right side for the four test subjects, and this was true for both the B81 and the Intenso. When the lowest difference between the left and right sides was examined, the positions varied for each of the four test subjects. Primarily the positions on the ipsilateral side of the head which are central, anterior and posterior performed well. Although, the ipsilateral posterior had a difference of approximately 8 dB for the highest and lowest mean when measuring with the both devices. This could be compared with the ipsilateral eyebrow where the difference was approximately 3 dB and 1.7 dB for the B81 and Intenso. The positions with the lowest SD, where each side counts as one measurement, between the subjects were the ipsilateral eyebrow for the B81 and the ipsilateral central, anterior and posterior for the Intenso. The earmuff does not seal perfectly, and sound leakage might occur, especially when measuring the eyebrows for the Intenso. An enhancement for future studies could be to investigate how much the sound leakage and the pressure of the SM and earmuff affect the result of the measurements.

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A

Appendix 1

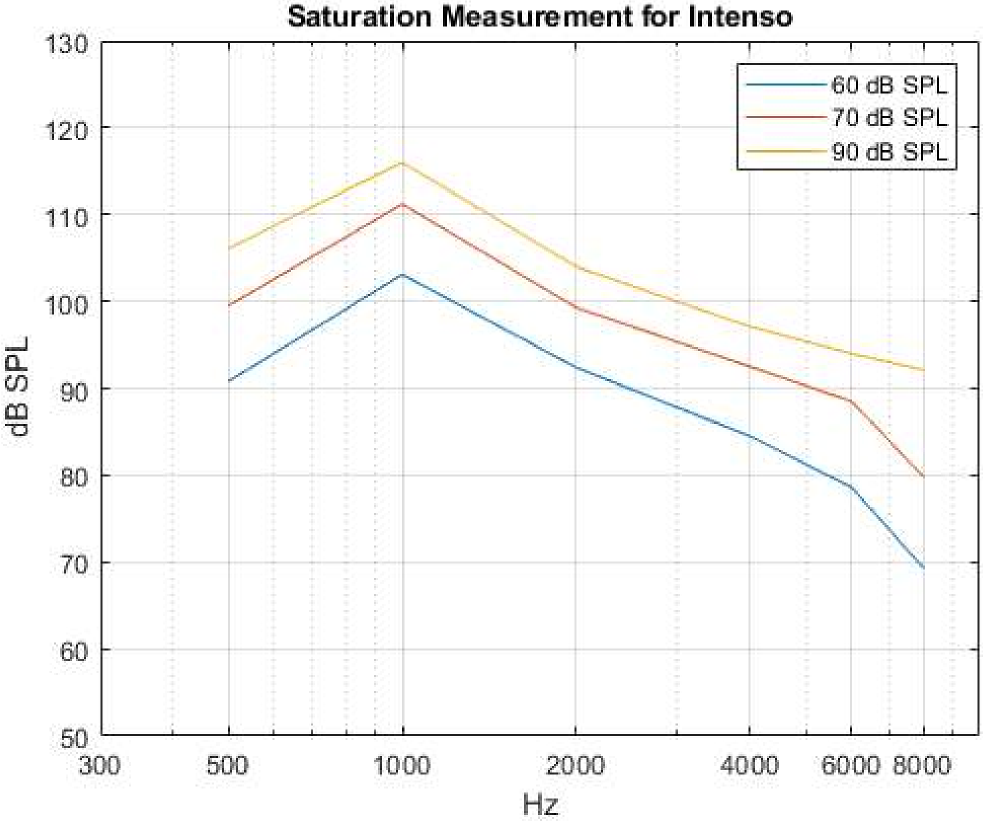

Figure A.1: Plot from the saturation measurements on the Intenso.

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