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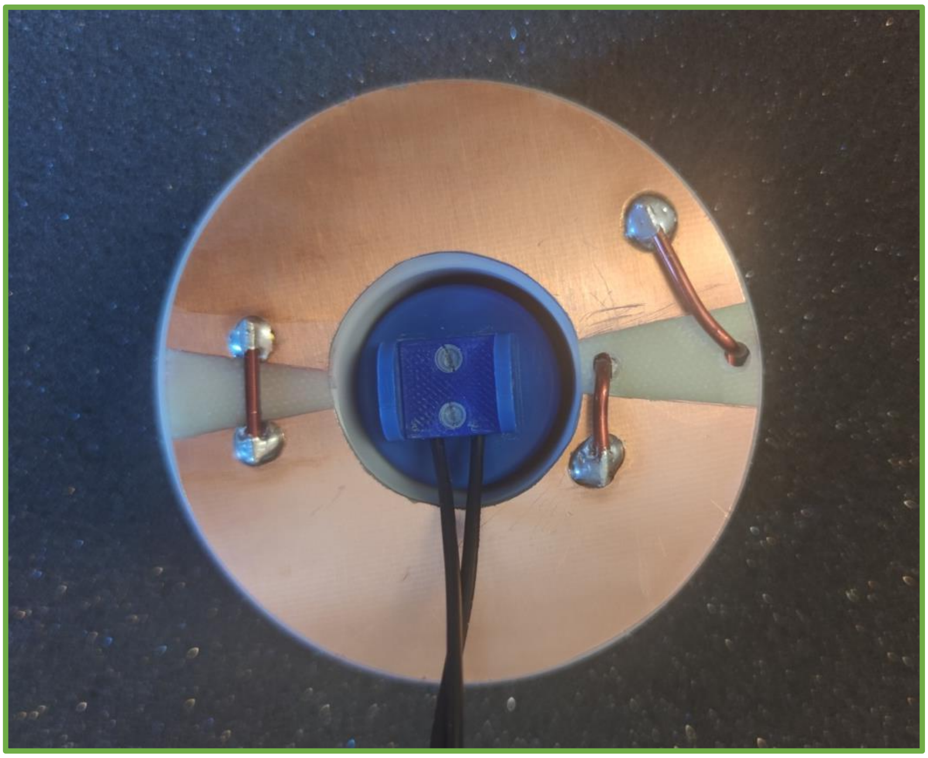

Reduction of Electromagnetic Artefact from Bone Conduction Transducer

Bachelor's Thesis in Electrical Engineering

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Evaluation of a new method aimed to reduce electromagnetic disturbance in hearing and balance diagnostics

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Cover: Bone conduction transducer, B250, placed inside the bobbin coil.

PREFACE

This project, as part of our bachelor's thesis in Electrical Engineering, was carried out at the Department of Electrical Engineering (*Chalmers University of Technology*) in the small, but very efficient, Hearing Research Lab. Normally, the unit of Biomedical Signals and Systems conducts their research in these facilities. During the spring of 2020, we had the opportunity to use the Hearing Research Lab to complete the practical part of our bachelor's thesis, which consists of 15 credits in total.

We would like to thank our examiner Karl-Johan Fredén Jansson for his help introducing us to the lab equipment and helping us throughout the project with various practical problems, including software download and hardware calibration. We would also like to thank our supervisor, Bo Håkansson, for his help introducing us to the subject and giving us valuable tips during the practical part of the project. The bobbin coil prototype was designed by Thomas Rylander at the Department of Electrical Engineering, whom we would also like to thank. Lastly, we would like to thank Sabine Reinfeldt for informing us about this project.

Viktor Edlund & Alexander Hasselström

Chalmers University of Technology

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ABSTRACT

In audiometry and balance diagnostics, bone conduction (*BC*) transducers can be used as a stimulating tool to evoke neurological responses in patients, through transmission of sound to the inner ear via the skull bone. The neurological response is recorded, using surface electrodes, and interpreted in order to objectively assess hearing- and balance abilities. A recurring problem within BC audiology, is that the transducers emit large amounts of electromagnetic radiation while operated on low frequencies, that in turn induces a voltage across the measuring electrodes (*Artefact*). Consequently, the recorded response might be concealed due to the electromagnetic artefact, thus complicating the interpretation process.

The new transducer prototype B250, introduced by professor Bo Håkansson in 2018, offers many enhancements compared to previous conventional models, including reduced electromagnetic radiation. Still, improvements, in particular further reduction of its electromagnetic radiation, may be needed if the B250 is to be applied in all types of relevant clinical investigations. Therefore, a research group within the Department of Electrical Engineering are looking into a new method of reducing the influence of electromagnetic artefacts in BC audiology. The new method is based on a bobbin coil designed to enclose the B250 and dampen its emitted radiation, by generating a counteracting electromagnetic field. This study aims to evaluate the new method, through a series of synthetic ABR and VEMP measurements carried out on an artificial head, followed by a short series of real ABR measurements performed on one human subject. By comparing the results obtained from different test configurations with and without the bobbin coil attached, the aim was to draw conclusions regarding the efficiency of the method.

The results obtained in this study indicate a reduction of the electromagnetic artefact in all synthetic test configurations, however, a wide variation in percentual reduction was noticed. Reductions were also obtained in human ABR, in pilot tests where a comparison was possible. It was also found that the bobbin coil reduces the electromagnetic artefact more efficiently using 250 Hz rather than 500 Hz stimuli. We believe that these results support the benefit of using the bobbin coil as a supplementary component to the B250. Still, repeated measurements are needed to verify the results obtained in this study.

Key words*: Audiology, Audiometry, Vestibular testing, Transducer, Bone Conduction (BC), VEMP, ABR.*

SAMMANFATTNING

Inom audiometri och balansdiagnostik kan benledare användas för att framkalla neurologiska svar hos patienter genom ljudöverföring via skallbenet till innerörat. Den neurologiska aktiviteten registreras med hjälp av ytelektroder och tolkas för att objektivt bedöma hörsel- och balansförmågor hos patienter. Ett återkommande problem inom benledningsdiagnostik är den elektromagnetiska strålningen som benledarna alstrar vid låga frekvenser. Det magnetiska fältet, som utstrålas från benledaren, ger upphov till en inducerad spänning i mätelektroderna som följaktligen kan dölja det eftersökta neurologiska svaret och på så vis försvåra tolkningsprocessen.

År 2018 presenterade professor Bo Håkansson (*Institutionen för elektroteknik, Chalmers tekniska högskola),* en ny benledarprototyp vid namnet B250. Denna modell medför många förbättringar i jämförelse med tidigare konventionella benledare, bland andra en reducerad elektromagnetisk strålning. Trots dessa framsteg önskas ytterligare förbättringar av B250-modellen, om den ska användas i alla relevanta tillämpningar gällande klinisk diagnostik i framtiden. I synnerhet önskas ytterligare reduktion av dess elektromagnetiska strålning. Forskningsgruppen för medicinska signaler och system, vid institutionen för elektroteknik (Chalmers), har utvecklat en ny metod för att minska påverkan av elektromagnetiska artefakter från benledare vid hörsel-och balansdiagnostik. Denna metod är baserad på en spole lindad på en bobbinstomme som har dimensionerats för att perfekt omsluta benledarprototypen B250, utan att störa dess elektromekaniska funktion. Bobbinstommen, som innehåller en kortsluten spole, genererar ett motverkande magnetiskt fält som släcker ut delar av det störande magnetfältet som utstrålas från benledaren. I denna studie utvärderas den nya metoden genom en serie syntetiska ABR-och VEMP-mätningar utförda på ett artificiellt huvud. De syntetiska mätningarna följs upp av en kort serie ABR-mätningar utförda på ett mänskligt testobjekt. Mätningarna utförs med och utan bobbinstommen påkopplad, för att kunna urskilja eventuella minskningar av den elektromagnetiska strålningen.

De syntetiska mätningarna resulterade i en tydlig reduktion av den elektromagnetiska störningen i samtliga mätkonfigurationer, dock med en stor variation mellan mätningarna. Procentuella minskningar av störningen erhölls även i de efterföljande ABR-mätningarna utförda på en människa, i samtliga tester där fallen med och utan bobbinstommen kunde jämföras. Bobbinstommen minskar också störningen mer effektivt när benledaren matas med 250 Hz än 500 Hz. Vår slutgiltiga bedömning, utifrån de erhållna resultaten, är att bobbinstommen har gynnsamma effekter när den används som ett komplement till benledarprototypen B250. Dock krävs upprepade och mer omfattande mätningar för att verifiera de resultat som erhållits i denna studie.

***Nyckelord**: Audiometri, Balansdiagnostik, Audiologi, Benledare, VEMP, ABR.*

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TERMINOLOGY AND ABBREVATIONS

AC - Air conduction.

BC – Bone conduction.

Cochlea- The main hearing organ of the inner ear.

Tone burst – Short harmonic signal.

Chirp –Signal that sweeps over a desired range of frequencies.

BPPV (Benign Paroxysmal Positional Vertigo) – Common vestibular disorder. Causes vertigo and dizziness.

Acoustic Neuroma – Tumor that develops in the inner ear. Causes dizziness and loss of balance.

Ménière's disease – Disease that causes vertigo, tinnitus, fluctuating hearing.

BEST – Balanced electromagnetic separation transducer.

ABR - Auditory Brainstem Response.

VEMP - Vestibular Evoked Myogenic Potential

Vestibular testing – Methods for assessing the function of the balance organs.

Total Harmonic Distortion (THD) – Relative measure of amount of distortion in harmonic signals.

dB HL - Decibel Hearing Level.

dB nHL – Decibel normalized hearing level.

Sensorineural HL - Impairment situated in the inner ear.

Conductive HL – Impairment situated in the outer or middle ear.

BAHA - Bone anchored hearing aids.

Auditory perception – Ability to receive and interpret sound.

Otosclerosis – Abnormal bone growth in the middle ear.

Otitis media – Infection in the middle ear.

Vertigo – A sensation of spinning or swaying

Transducer – A device that converts one form of energy into another.

cVEMP – Cervical VEMP.

oVEMP – Ocular VEMP.

SPL – Decibel Sound Pressure Level.

RETVFL – Reference Equivalent Threshold Vibratory Force Level.

Psycho-motoric dysfunction – Impairments in muscle function and speech due to disruptions in connections between brain and muscle functions.

MRI – Magnetic Resonance Imaging.

Tympanic cavity – Cavity surrounding the bones of the middle ear.

Endolymph – A fluid contained in the inner ear.

Vestibular system – Sensory system in the inner ear providing the brain with information about motion and position.

Otolithic Membrane – Fibrous structure in the vestibular system of the inner ear.

Ipsilateral - On the same side of the body.

Contralateral - On the opposite side of the body.

Bilateral - Pertaining to both sides.

Audiology - The science of hearing and balance.

Audiometry - Subdivision in Audiology which relates to measuring hearing abilities in different ways.

IOM - Inferior Oblique muscle.

SCM - Sternocleidomastoid muscle.

Mastoid - One part of the temporal bone located behind the ear.

1. INTRODUCTION

The human ear is a complex and sensitive system. Auditory perception and sense of balance are abilities managed by different organs and subsystems that form the human ear. Sound waves, or variations in air pressure, are transmitted via the ear canal to the hair cells in the cochlea. The signals are then transmitted to the brain, via the auditory nerve, where they are interpreted as the sound that we perceive. This is commonly referred to as hearing through Air Conduction (*AC*). However, perhaps unknown among the general public, sound also propagates through the skull bone. These vibrations stimulate the cochlear hair cells with the skull bone as transmission medium, thus bypassing the middle and outer ear. Transmission and perception of sound through skull vibration is referred to as Bone Conduction (*BC*) hearing. The combination of AC and BC hearing forms the hearing sense. Unlike auditory perception, where the end organ is the cochlear hair cells, the sense of balance is dependent of receptors located in the vestibular labyrinth. These receptors provide the brain with essential information about motion and position; allowing humans to keep balance and maintain posture [1]. Similar to the hearing organs, the balance receptors can detect AC and BC signals from the surroundings.

Due to the complexity and fragility of the ear, there are numerous diseases that may affect the various organs of the ear, thus affecting hearing and balance abilities. Hearing loss, which is a partial or total impairment of a patient's hearing ability, can be a result of various conditions such as: chronical ear infections, Otosclerosis and malformation of the ear [2]. Disorders related to the balance system include SSCD, BPPV, Acoustic Neuroma and Ménière's disease, where symptoms range from loss of balance to vertigo and dizziness [3]. Impairments of hearing- and balance abilities, naturally, reduce the quality of life for those affected. Severe cases of Acoustic Neuroma can even be fatal if left unnoticed and untreated [4]. Consequently, the development of effective diagnostical methods and suitable treatment for ear-related disorders is of great importance.

During the 20th century, new technology emerged that utilized the BC phenomenon in hearing aids and audiometric testing devices. The development of electro-mechanical BC transducers made it possible to generate and transmit vibrations through the skull bone. By utilizing electromagnetic phenomena, these devices can translate an alternating current into an oscillating motion that causes sound vibrations in the skull bone. BC vibrators paved the way for new and improved hearing aids, that are today widely used among patients suffering from conductive hearing loss [5].

As stated above, BC transducers are proven to be advantageous in diagnostical applications as well, such as Auditory Brainstem Response (*ABR*) investigations. ABR, which is an established diagnostical method of assessing cochlear function, measures the auditory nerve response to AC and BC stimuli. Another potential medical application of BC transducers, is within vestibular testing. Vestibular Evoked Myogenic Potential (*VEMP*) is a relatively new procedure in balance diagnostics, in which BC transducers can be applied as a stimulating tool to evoke involuntary muscular response [6]. Muscular responses in VEMP are caused by a reflex that allows human beings to restore posture and head position after sudden spatial movement [6]. These muscular responses can be recorded and analyzed in order to assess function of the balance organs. VEMP and ABR tests are generally performed using AC stimuli, however, research indicates that BC stimuli has many advantages compared to the former. For example, a considerably lower decibel level is required to evoke viable response in BC VEMP than in AC VEMP [6].

Being able to use one BC transducer for both ABR and VEMP would be ideal, since it is independent of the condition of the middle ear. This would also enable a simple, objective and effective way to diagnose balance and hearing impairments, without exposing the patient to the harmfully loud sound that come with AC stimulation [6]. Since ABR and VEMP measures neurological response and does not require the patient to be actively involved, they can be performed on infants and patients with psycho-motoric dysfunction [7]. Using BC stimulated VEMP and ABR could also, for instance, result in less MRI scanning in healthcare, which is an effective, but expensive method of identifying Acoustic Neuroma. Research and development within audiology has led to the understanding that suitable frequencies for VEMP applications are in the lower regions of the human hearing range, where humans appear to have a greater sensitivity to stimuli [8]. However, a recurring problem in both BC ABR and BC VEMP diagnostics is the occurrence of electromagnetic disturbances in recordings, when applying low stimuli frequencies [7] [6]. The electromagnetic field, that causes the transducer to vibrate, spreads around the transducer and induces a voltage in the measuring electrodes. As a result, the induced voltage hides the recorded neurological response and complicates the interpretation process [7]. When performing BC ABR on small children, these disturbances have an even larger impact on the recordings since the electrodes must be placed close to the vibrator.
The electromagnetic artefacts that occur in VEMP and ABR recordings is an issue that calls for further development of BC transducers, to improve their performance and applicability in clinical settings.

1.1. Background

The B250 transducer model, introduced by professor Bo Håkansson et al. in 2018, is a vibrator prototype optimized for 250 Hz stimuli [6]. Compared to previous conventional transducers, the B250 provides higher output power and generates less electromagnetic radiation [7]. Furthermore, the B250 can evoke viable VEMP responses to a greater extent than the previous B81 transducer model, when operated at 250 Hz [6]. A reduction of electromagnetic radiation is achieved with the B250, in comparison to the B81, but a further reduction is desirable in clinical settings.

The Biomedical Signals and Systems research group at the Department of Electrical Engineering, Chalmers University of Technology, are looking into a new method aimed to reduce the effect of electromagnetic artefacts from the B250 in VEMP and ABR measurements, thereby improving its applicability in hearing and balance diagnostics. This method is based on a bobbin coil prototype that is designed to enclose the B250 transducer. The bobbin coil is meant to act as an electromagnetic shield that cancels out parts of the electromagnetic radiation originating from the enclosed B250 transducer. Theoretically, the coil will generate a reversed electromagnetic field that counteracts and attenuate the field arising from the B250. Applying this method can theoretically result in a 25% reduction of magnetic flux density at a radius of 5 centimeters from the vibrator, according to calculations provided by the Department of Electrical Engineering.

1.2. Purpose

In order to determine whether this method is effective or not, a series of measurements will be performed using the B250 and the bobbin coil prototype. By implementing an experimental methodology and analyzing its results, the aim of this project is to draw conclusions on whether the bobbin coil principle is effective or not. This project aims to provide useful information for further research and development of BC transducers, and supplementary hardware components.

1.3. Limitations

This evaluation is mainly based on a set-up of existing prototypes; a bobbin coil and the bone conduction transducer B250. This report does not include calculations and design concepts of a further developed version of the bobbin coil. All equipment, such as hardware components and software tools, is provided by the Department of Electrical Engineering and has been used in similar projects. Consequently, there is no reason to consider alternative or additional equipment. The B250 transducer was supported by Ortofon A/S (Nakskov, Denmark) and the Eclipse system by Interacoustics A/S (Middelfart, Denmark).

The main focus of this project is to evaluate the Bobbin coil principle by performing synthetic ABR and VEMP measurements on an artificial head – in this case, a watermelon. A watermelon is used to simulate some properties of a human head, in particular, it has similar form/shape and electrical impedance as the skin. In the main experimental phase, measurement and interpretation of neurological response to stimuli is therefore, naturally, impossible and irrelevant. What differs between the synthetic ABR and VEMP measurements, is mainly the placement of the electrodes and the B250 transducer. However, a final limited ABR test series is performed on a human subject in order to assess the functionality of the bobbin coil in real measurements. In the final phase, human response to stimuli will be regarded and analysed. The analysis comprises of observation and comparison between typical waveforms and the recorded ABR responses, in order to determine whether an ABR response is in fact present. Since real VEMP measurements are not performed in this study, it is irrelevant to discuss the interpretation of human VEMP response.

1.4. Problems

The aim of this project is to answer the questions listed below:

I. Does the bobbin coil reduce the electromagnetic radiation that originates from the B250 transducer?

II. Does the bobbin coil cause a reduction of the electromagnetic radiation, that corresponds to the theoretical estimation? (*25% reduction 5 cm from the transducer*)

III. Does the bobbin coil reduce the electromagnetic disturbance in real ABR measurements as well?

IV. Is the reduction of such significance that it calls for further study and development of the bobbin coil as a supplementary component?

2. THEORY

In this section, a theoretical description of the human ear and diagnostical methods treated in this study, is presented. Furthermore, technical descriptions of the devices used, as well as the appearance of electromagnetic artefacts, are presented below.

2.1. The Human Ear

This section aims to provide a detailed description of the human ear: hearing sense and sense of balance.

2.1.1. Auditory system

The auditory system is usually divided into three main components: the outer ear, the middle ear and the inner ear. The pathway of air conducted sound is described in the following way. Sound waves, or variations in air pressure, spread through the surroundings before they eventually reach the outer ear. Similar to a funnel, the pinna directs the incoming sound waves into the ear canal (*Figure 2.1*). The pinna also provides the brain with essential information about the direction of the incoming sound, with its reflecting and attenuating properties [9]. Once the sound waves have entered the ear canal, they eventually hit the tympanic membrane (*eardrum*) that marks the beginning of the middle ear (*Figure 2.1*). As the sound waves hit the pressure sensitive tympanic membrane, it starts to vibrate.

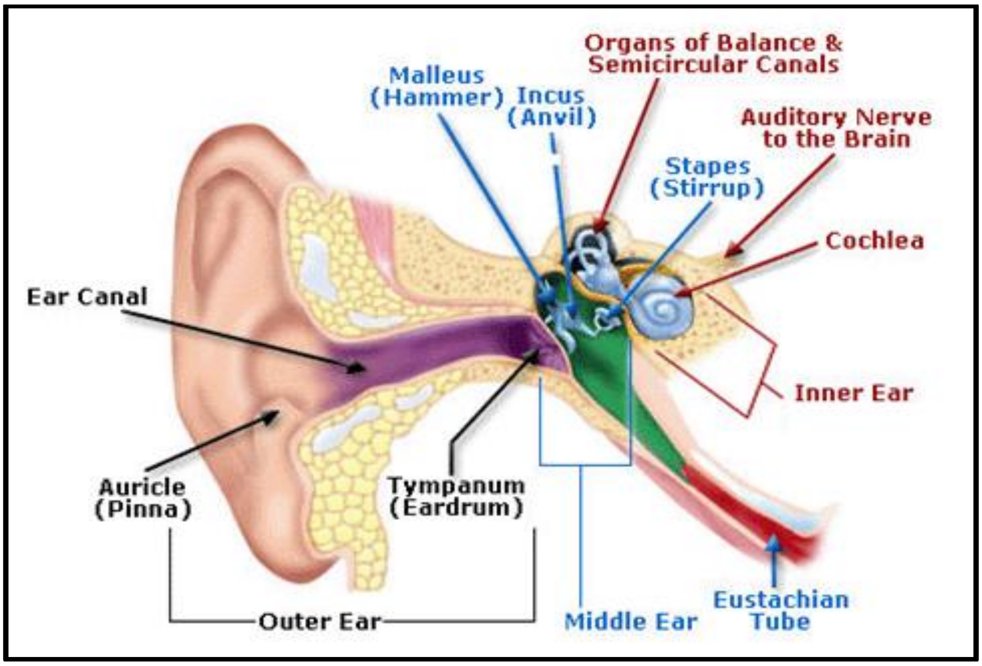

Figure 2.1. Anatomy of the ear. From [10].

Attached to the tympanic membrane are three interconnected bones called the ossicles (*Malleus, Incus, Stapes*), located in the tympanic cavity. Sound vibrations in the tympanic membrane causes the chain of ossicular bones to move. The ossicles amplify the sound vibrations from the tympanic membrane, while transferring them further into the ear [11]. At the other end of the ossicular chain, the Stapes bone is attached to the oval window. The oval window, which marks the end of the middle ear, is a membrane that covers the entrance of the cochlea (*inner ear*). As the sound vibrations are transmitted via the ossicular chain, the Stapes bone starts pushing the oval window back and forth, causing the endolymph fluid in the cochlea to move in a wave-like manner [12]. Depending on the frequency and amplitude of the incoming sound wave, different receptors called hair cells are stimulated by the moving fluid. Stimulation of the hair cells generates neural impulses that are transmitted via the nerve fibers to the auditory nerve [13]. Each hair cell is dedicated to a narrow band of frequencies, which allows human beings to hear sound from a wide range of frequencies [12]. It is normally said that healthy human beings can perceive sound ranging from 20 to 20 000 Hz [14]. The cochlea is of tonotopic structure; meaning that low frequencies are registered at its center (*Apex*) while high frequencies are detected at the base, close to the entrance of the cochlea [15]. Neural impulses, that are results of hair cell stimulation, gather in the auditory nerve, through which they are transferred to the brain. In the brain, these signals are processed and interpreted as the sounds we perceive.

Perceiving sound that is transmitted through the ear canal, via the middle ear, is normally referred to as hearing through Air Conduction (*AC*). However, there are alternative ways of conducting sound to the cochlea. In Bone Conduction (*BC*) hearing, the cochlear hair cells are stimulated by sound vibrations transmitted through the skull bone. Since BC sound propagates through the skull bone, they bypass the middle and the outer ear (Figure 2.1).

Hearing loss, which is partial or complete inability to hear, can be a result of various ear related disorders. Hearing loss caused by disorders located in the middle ear or the outer ear, is commonly referred to as conductive hearing loss. A sensorineural hearing loss, on the other hand, is a hearing loss caused by an impairment in the inner ear. A few examples of common conductive and sensorineural disorders are briefly described below:

Conductive hearing loss:

- *Otitis media* – Infection in the middle ear that may obstruct movement of the tympanic membrane and the ossicles [2].
- *Otosclerosis* – Abnormal bone growth in the middle ear that obstructs sound transmission [2].
- Malformation of the outer or middle ear structure.

Sensorineural hearing loss:

- Noise induced hearing loss.
- Age related hearing loss.
- *Autoimmune inner ear disease (AIED)*- bilateral sensorineural HL due to uncontrolled immune system response [18].
- Malformation of the inner ear.

2.1.2. Vestibular system

The vestibular system is a complex structure, comprising of various cooperating organs that manage the sense of balance. Commonly, the vestibular system is divided into two main components: the central system and the peripheral system [19]. This description focuses on the peripheral system, which consists of the vestibular apparatus and associated neurological paths to the to the brain.

Two main structures form the inner ear: the cochlea, related to the hearing sense, and the vestibular apparatus, responsible for the sense of balance [19]. The vestibular apparatus provides the brain with essential information about motion and spatial orientation through a complex process. Similar to the cochlea, the vestibular apparatus can be stimulated by AC and BC signals from the surroundings.

Located in the semicircular canals, are receptors (*hair cells*) similar to those in the cochlea (*Figure 2.2*). During angular movement, the endolymph fluid in the semicircular canal is pushed around, causing the hair cells to bend. When the hair cells bend, neural impulses are transmitted through the nerve fibers to the vestibular nerve. These three semicircular canals are positioned approximately 90 degrees to each other, which enables perception of angular motion around the vertical, lateral and sagittal axis [19].

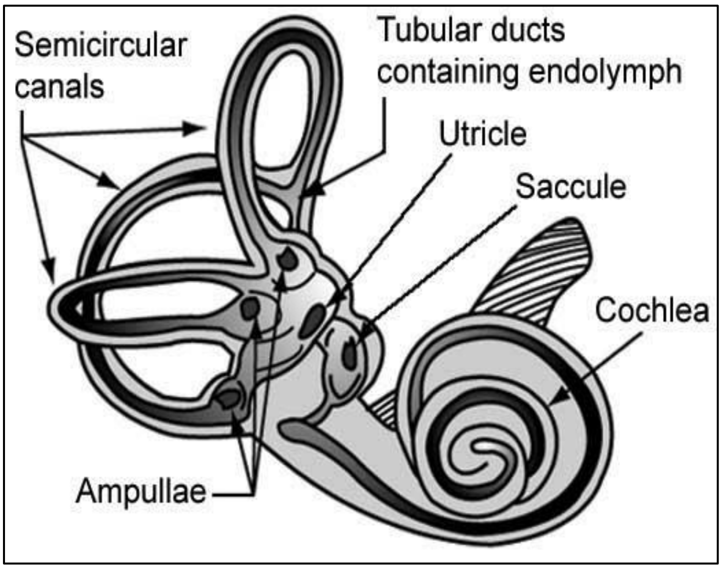

Figure 2.2. The vestibular system. From [20].

Additionally, the Utricle and Saccule, also referred to as the Otolith organs, form the second main component of the vestibular apparatus: the Vestibule. Their main task is to provide the brain with information about acceleration and deacceleration in the horizontal and vertical planes. The Utricle senses linear motion primarily in the horizontal plane while the Saccule mainly senses altering linear motion vertically [19]. Attached to the surface of the gelatinous membrane, that surrounds the hair cells of the otolith organs, there are small calcium carbonate crystals called Otoconia (*ear rocks*). These ear rocks are essential since they enable the Saccule and Utricle to sense the gravitational force. While tilting your head, the gravitational force causes movement of the ear rocks and the otolith membrane. This, in turn, bends the hair cells [19]. Stimulation of the hair cells generates neural impulses that are transmitted to the brain via the vestibular nerve.

The hair cells located in the Utricle and the Saccule, along with otolithic membrane and the Otoconia, are stimulated as long as there is a change in linear motion. While moving with a constant velocity, for instance, while you are at cruising altitude during a flight, the hair cells are not stimulated [19]. When the receptors do detect changes in linear motion, i.e. during take-off, the neural impulses are transferred through the nerve fibers to the vestibular nerve. The information coming from the semicircular canals and the otolith organs, through the vestibular nerve, are transmitted to the brain where they are processed and interpreted. Using this information, the brain transmits the needed neural impulses to the muscles in order to maintain balance and stability [19].

Similar to the auditory system, the vestibular system consists of numerous sensitive organs that can be affected by different disorders As a result, impairments of balance abilities occur. A few disorders and their associated symptoms, related to the vestibular system, are listed below:

- **Labyrinthitis** – infection in the inner ear that affects the vestibular nerve. Does not affect hearing. Symptoms: dizziness or vertigo [3].
- **BPPV (Benign Paroxysmal Positional Vertigo)** – Dislodgment of otoconia in the otolith organs, causing transmission of false signals to the brain. Symptoms: imbalance and/or **vertigo** [21].
- **Schwannoma** – a tumor on the vestibular nerve.
- **Ménière's disease** – A disorder caused by fluid accumulation in the vestibular labyrinth. Causes hearing loss and/or vertigo in patients [17].
- **SSCD (Superior Semicircular Canal Dehiscence) –** An opening/window in the bone overlaying the superior semicircular canal of the inner ear. Symptoms: Sensitive to low frequency sound, can hear body sounds and eye movements. Experience vertigo when exposed to loud sound, during rapid movement and/or when coughing.

2.2. Diagnostic methods

To assess hearing and balance abilities in patients, different diagnostical methods are applied. In the following sub-section, a detailed description of the ABR procedure is presented, followed by a brief explanation of the VEMP methodology.

2.2.1. ABR

Auditory Brainstem Response (ABR) is a diagnostical method that aims to assess hearing abilities in patients by recording and analyzing neurological response to AC and BC stimuli. Surface electrodes are attached to the patient in order to measure the electrical activity in the pathway between the cochlea and the brain, that come as a result of AC or BC stimuli. ABR is an objective way of assessing hearing abilities in patients since it does not require them to be actively involved. Patients who are unable to participate in traditional behavioural audiometry, for instance, infants or patients with psychomotor impairment, can therefore be objectively be diagnosed using ABR. ABR is also known to provide accurate results that are comparatively easy to interpret [7].

ABR can be evoked using various types of stimuli. Tone bursts and chirps are among the most commonly used stimuli types in ABR. A tone burst is a brief tone consisting of an arbitrary number of periods of a fixed frequency, usually multiplied with a window function such as a Blackman window. A chirp signal on the other hand, sweeps over a desired range of frequencies, with an increasing or decreasing period time. In ABR applications, chirp signals have been refined throughout the years which has resulted in the narrow-band level specific chirp (*NB LS CE-chirp ®).* The NB LS CE-chirp® was specifically developed to obtain better ABR recordings and simplify the interpretation of the results [22]. Neurological signals measured in ABR are very small but can be increased if many cochlear hair cells are stimulated synchronously. However, due to the tonotopic organization of the cochlear hair cells, there are different travel times for each frequency component within the stimulus. The NB LS CE-chirp® compensates for the differences in time travel for each frequency component using in-built timing functions, thereby maximizing the synchronous neural activity in the auditory nerve. As a result, the critical components of the ABR response are enhanced; making them easier to distinguish. Additionally, the NB LS CE-chirp ® offers a reduced test time [22]. The narrow-band (NB) feature offers a more frequency specific chirp signal. Furthermore, the level specific feature (LS) offers an optimized stimulus for 20 different intensity levels ranging from 0 to 100 dB nHL (*normalized Hearing Level*) [15].

In audiology, hearing thresholds are commonly determined using the intensity scales dB HL or nHL, which are normalized logarithmic scales that relates to the hearing level of normal subjects in order to simplify hearing and balance investigations. The dB nHL scale is based on time limited non-tonal signals whereas the more commonly used dB HL scale is based on continuous signals. In both scales, the Sound Pressure Level (*SPL*) is adjusted to be more useful in audiology applications [23] [24]. In the dB SPL scale, a reference value of 20 µPa in sound pressure is used as reference throughout the frequency range, in order to determine threshold values. Young individuals with healthy ears perceive the quietest possible sound pressure level at 20 µPa (1 kHz), hence this level is chosen as a reference (*0 dB SPL*) [24]. However, humans do not possess the same hearing abilities on all frequencies. In dB HL (*Hearing Level*), the reference value is frequency dependent; meaning that the reference for each frequency is the quietest sound pressure level that a group of individuals with normal hearing can experience.

Conventionally, hearing thresholds are determined at frequency octaves: 500 Hz, 1 kHz, 2 kHz and 4 kHz. Modern bone conduction devices do however offer a chance to perform ABR with a stimuli frequency of 250 Hz as well [25]. If the neurological response is not viable at a certain frequency and intensity level (dB nHL), the intensity is increased in small steps until a viable response has been found; meaning that a hearing threshold has been found for a specific frequency. This information is used in order to assess hearing function and, if needed, find an appropriate rehabilitation method.

The measured response in ABR has relatively small amplitudes. Therefore, when performing ABR, the placement of the electrodes as well as the contact between electrodes and skin surface, are important factors. In order to obtain feasible recordings, electrodes should be placed in the following way [26]:

- **(-) Inverting electrodes:** One on each earlobe or mastoid.
- **(+) Active electrode:** Vertex or high forehead.
- **Ground electrode**: lower forehead, a few centimeters below the active electrode.

In BC ABR, the transducer is placed on right or left mastoid [27]. The two inverting electrodes enable measurements on both ears simultaneously. If stimulus is applied on the right mastoid, one can measure the neural activity in the right auditory nerve (*Ipsilaterally*) as well as the neural activity on the left side (*Contralaterally*). Before the electrodes are attached to the patient, it is important to prepare the skin surface by cleaning it thoroughly. This is done in order to obtain low electrode impedances.

An ABR response is considered to be viable if it corresponds to a certain waveform pattern, consisting of a series of peaks occurring with different latencies (Figure 2.3). The waveform consists of wave I to VII, but its appearance differs to some extent depending on literature. Latency of each waveform component (I-VII) is described as the time interval between stimulus onset and peak appearance, while the interpeak latency refers to the delay between peaks. The fifth peak (*wave V*) is considered to be of great clinical value and is therefore a critical component in analysis of ABR recordings [28].

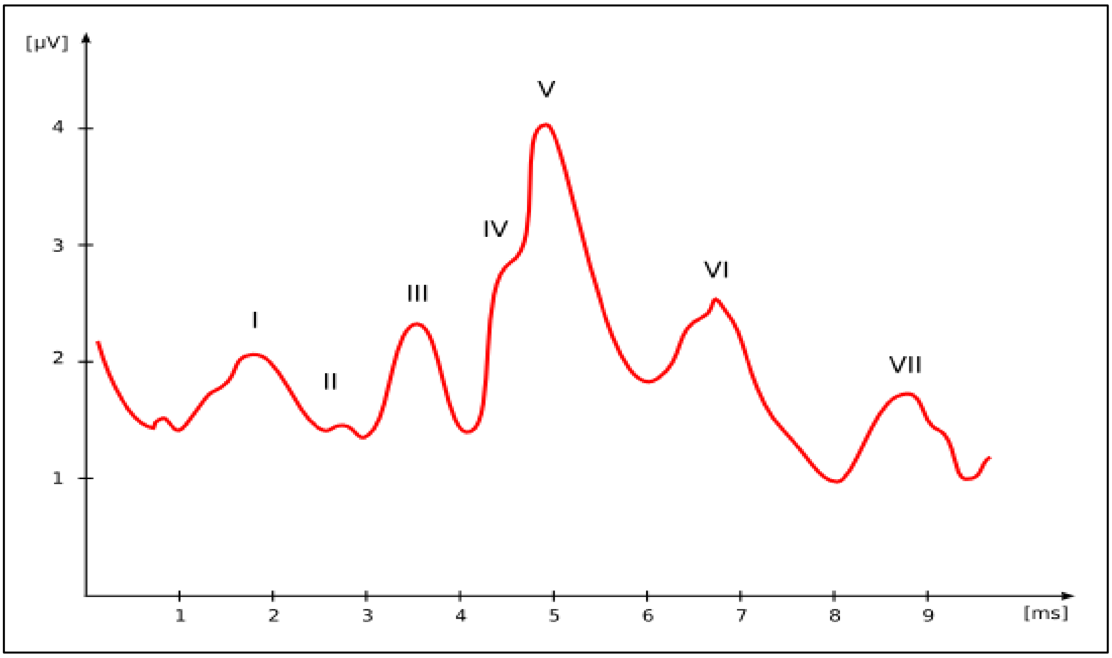

Figure 2.3. ABR response consisting of peaks I – VII. From [29].

Latencies and amplitudes of the ABR response are dependent of various stimuli parameters such as: frequency, intensity, contralateral or ipsilateral stimuli and signal waveform (*Tone burst, chirp, click et cetera*). Additionally, BC ABR latencies are estimated to be 0.16 to 0.88 milliseconds longer than those in AC ABR [30]. Another important factor to consider is the number of averages calculated from the recordings. In ABR, the number of recordings range from 1000 to 4000 [28], from which an average is calculated. This enables effective filtering of random noise and provides a more distinct recorded waveform.

Although ABR is considered to be a relatively objective diagnostical method, the conventional technique in determining threshold values is still based on visual estimation [31]. Since waveform patterns differ depending on type of stimuli, it can be challenging to determine whether an ABR response is in fact present.

Since BC vibrators apply a vibratory force to the skull bone, instead of generating variations in sound pressure (AC), a different scale is used as reference in BC audiometry. Hearing thresholds relate to Reference Equivalent Threshold Vibratory Force Levels (*RETVFL*) where each relevant frequency has a corresponding threshold value in dB RETVFL, relative to 1 µN. These threshold values are the intensities at which a large number of people with normal hearing can perceive sound through skull vibration [32].

A recurring challenge in BC audiometry is that different transducers provide variating output force levels depending on the frequency, envelope and waveform of the stimuli signals. Due to this fact, it is essential that the BC transducer is calibrated so that the output force level corresponds to the current standards regarding audiometric zeros. Therefore, a correction value is added to - or subtracted from - the input intensity level, in dB HL.

In adult patients, AC evoked ABR can be used in combination with BC ABR to determine whether the hearing loss is conductive or sensorineural. Firstly, AC stimulation is applied, and if the response indicates a hearing loss, BC stimulation is tested. As stated in the description of the auditory system, BC sound bypasses the middle and outer ear through the skull bone. So, if BC evoked ABR does not indicate a hearing loss, the hearing loss is assumed to be conductive [7]. However, when performing ABR on infants and small children, this strategy may be problematic. In this context, AC evoked ABR on patients with a conductive hearing loss, can cause misleading results and wrong diagnosis. This situation requires BC evoked ABR as an alternative, since the obstruction is located in the middle or outer ear. A recurring problem with BC ABR in infants and small children is, however, that the electrodes must be placed closer to the transducer, where the electromagnetic radiation is greater. The magnetic flux originating from the transducer, induces a voltage across the electrodes that is normally much greater in amplitude than the sought ABR response. As a result, the neural response is concealed by the electromagnetic artefact which leads to interpretation difficulties. Due to this problem, BC evoked ABR is rarely used in hearing assessment on infants and small children [7].

Another issue that comes with AC stimulation is the harmfully high intensity levels that must be used in order to evoke VEMP response. In BC VEMP, the required intensity level is significantly lower, which reduces the risk of causing damage to the ears.

2.2.2. VEMP

Vestibular Evoked Myogenic Potential (*VEMP*) is a relatively new diagnostical procedure within vestibular testing, that aims to assess balance neurogenic pathways. Loud sound and skull vibration trigger human body reflexes, that activates muscular response in order to maintain balance through unexpected spatial movement [6]. Sound stimulation transmitted through the ear canal (AC) or the skull bone (BC), excite the hair cells located in the otolith organs; evoking neural reflex impulses that travel via the vestibular nerve to the brain. The brain processes the incoming signals and transmits neural impulses to the Inferior Oblique muscle (*IOM*); one of several muscles controlling eye movement, and the Sternocleidomastoid muscle (*SCM*); controlling head rotation. As a result, the muscles contract in order to restore posture and head position. Surface electrodes record the muscular activity in SCM or IOM muscles, caused by AC and BC stimulation. The recorded VEMP responses are analyzed in order assess vestibular function in patients. Abnormalities in VEMP responses have been reported in numerous diseases related to the vestibular system, which makes VEMP a powerful tool for investigating pathogenic vestibular disorders [33].

Ocular VEMP (*oVEM*P) relates to the muscular responses in the IOM. The signals measured in oVEMP is thought to reflect activation of the Utricle, while cVEMP is thought to reflect activation of the Saccule [6]. In BC oVEMP, the transducer is placed on the skin over a bony part of the skull, either on the forehead just beneath the hairline, or to the mastoid just behind the pinna. Surface electrodes are positioned in the following manner [6]:

- **(-) Inverting electrode:** Just beneath the eye.
- **(+) Active electrode:** Approximately 2 centimeters below the inverting electrode.
- **Ground electrode**: Upper rim of **sternum**.

Two inverting electrodes can be used in oVEMP to measure bilaterally. In that case, the inverting electrodes are placed just below the left and right eye whereas the active electrode is placed on the chin [26].

In cervical VEMP (*cVEMP*) investigations, the recordings are, as mentioned, thought to reflect activation of the saccular hair cells. The BC transducer is placed on the mastoid, just behind the pinna [6]. Neural impulses are recorded over the SCM muscles, using the following electrode arrangement [6]:

- **(-) Inverting electrode:** on the SCM muscle.
- **(+) Active electrode:** on the upper rim of sternum.
- **Ground electrode**: on the lower forehead.

Prior to electrode attachment, the skin surface must be thoroughly cleansed to obtain low electrode impedances, just as in ABR investigations.

VEMP response can be evoked using tone bursts with frequencies ranging from 250 Hz to 4000 Hz [26]. In VEMP, the number of averages taken is approximately 150-300 sweeps, which is relatively low in comparison to ABR. These tone bursts are often combined with a Blackman window function, or another similar envelope [26][6].

The main components in a VEMP recording are two consecutive peaks of opposite polarity, occurring at certain latencies. Appearance, latency and amplitude of the wave components, differ depending on whether oVEMP or cVEMP is being performed. By measuring the peak-to-peak amplitude between the two consecutive peaks, one can determine whether a threshold level (*dB nHL*) has been reached. The peak-to peak value must be at least two times greater than the noise variability in the pre-stimuli recording [6]. As in ABR, BC stimuli is preferable in VEMP, since it requires lower intensity levels and allows patients with conductive hearing loss to undergo investigations.

2.3 Bone Conduction Transducer

Today, BC transducers are extensively used in wide range of applications. These applications range from commercial audio equipment to hearing implants [6], such as the Bone Anchored Hearing Aid (*BAHA*) that has improved hearing abilities in patients suffering from conductive hearing loss [34]. Furthermore, BC transducers are used by audiologists to diagnose hearing and balance abilities in patients, as an alternative to AC stimuli [6]. This study focuses on BC transducers in diagnostical applications.

First of all, a device that converts energy from one form to another, is termed a transducer. Specifically, a BC transducer transforms electromagnetic energy into kinetic energy; mechanical vibrations, that carry information through the skull bone to the auditory nerve [35]. The following BC transducers, suited for diagnostical applications: B71, B81 and B250 are further described below.

Radioear Corporation, USA, manufactures the bone vibrator B71 for global use, which has been the most frequently used BC transducer in audiometry for a long time [36]. The B71 is a variable reluctance type transducer type that generates vibrations through changes of the internal reluctance, caused by an alternating current. More specifically, the internal magnetic circuit is separated with small gaps with small suspension springs attached, that allows variations of the reluctance when an alternating current is applied. The magnetic circuit comprises of a static magnet in the centre of the construction. When an alternating current is applied, the dynamic magnetic flux makes directional changes which in turn causes the outer circular plate to vibrate at the same frequency as the current. By attaching the transducer to a surface, the vibrations are transmitted into the adjoining medium, i.e. the skull bone. This principle is primarily used in audiometry for hearing thresholds tests [36].

Since the B71 was introduced in 1973, updates have been made to improve its performance, especially at low frequencies. Still, the B71 has well-known limitations in the low-frequency band. When stimulating at low frequencies, which is of interest in VEMP- and ABR testing, the B71 produces high harmonic distortion [7]. Consequently, the B71 is rarely used in BC diagnostics when performing measurements below 500 Hz [36]. Its well-known struggle at low-frequencies is a clear problem which led to new solutions.

To answer the need of a transducer with better low-frequency performance, the Balanced Electromagnetic Separation Transducer (*BEST*) principle was introduced by B. Håkansson in the early 2000s. Both B71 and B81 models are of variable reluctance type, however, the latter is based on the BEST principle that enables improved electro-acoustic performance at low-frequencies [35]. This construction achieves higher linearity, less total harmonic distortion (*THD*) and improved sensitivity in measurements [25]. A cross-sectional view of the BEST, with its symmetric design, is displayed in *Figure 2.4*. The construction consists of an upper- and lower row of a total of four permanent magnet. The permanent magnets of the top and bottom rows, are opposed to each other, resulting in a balanced static flux.

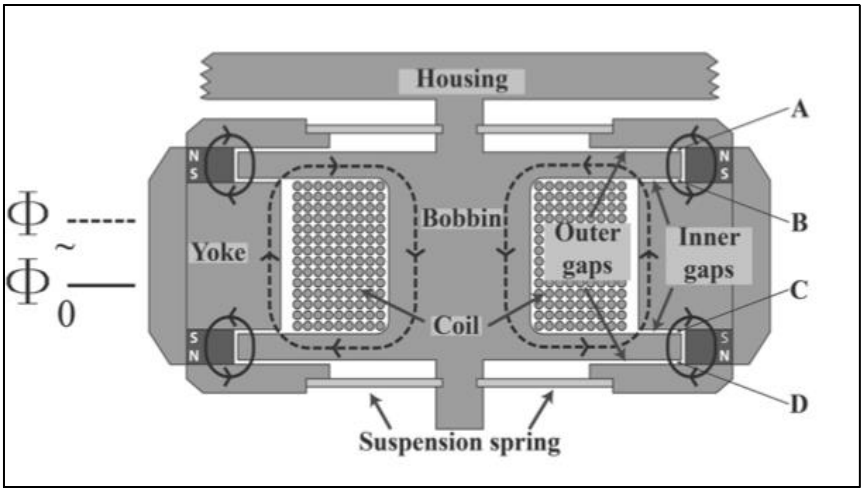

Figure 2.4. Cross-sectional view of the BEST design. A, D marks show the outer gaps and B, C show the inner gaps. From [35].

The following description is specified for one side of the transducer, due to its symmetrical design. As seen in figure 2.4, static- and dynamic magnetic circuits are marked with solid and dashed lines, respectively. Also seen in the same figure, the magnetic circuits are designed with both inner and outer gaps. In each gap, the permanent magnets generate a static flux Φ_{static} in opposite directions for the upper- and lower row. Moreover, the inner gaps are, in addition to this static flux, influenced by a dynamic flux Φ_{dynamic} from an applied AC current through a coil. Half of the dynamic flux flows through each side.

With the relation that force is proportional to the flux squared, it is possible to approximately calculate the total force in the following way [35]. This is accomplished by calculating the force in each gap and then adding all the forces. The force in the outer gaps, A, D in figure 2.4, is proportional to the static flow and approximated accordingly:

$$F_A \propto \emptyset_{static}{}^2 \text{ N} \qquad \text{(Equation 2.1)}$$

$$F_D \propto -\emptyset_{static}{}^2 \text{ N} \qquad \text{(Equation 2.2)}$$

Forces in gap A and D are opposed to each other, as described in the equations above. Furthermore, the force in the inner gaps, B and C, can be approximated accordingly:

$$F_B \propto \left(\emptyset_{static} - \frac{\emptyset_{dynamic}}{2}\right)^2 \text{N} \qquad \text{(Equation 2.3)}$$

$$F_c \propto -\left(\emptyset_{static} + \frac{\emptyset_{dynamic}}{2}\right)^2 \text{N} \qquad \text{(Equation 2.4)}$$

F_B and F_C are of opposite direction, as described in equations 2.3 and 2.4. To calculate the total force, all forces in each gap are added and multiplied by two, to include both sides:

$$F_{Total} \propto 2 \cdot (F_A + F_B + F_C + F_D) = \cdots = 4 \cdot \emptyset_{static} \cdot \emptyset_{dynamic} \qquad \text{(Equation 2.5)}$$

The result from equation 2.5 confirms that non-linearities are eliminated and therefore a desired linear behaviour is obtained. Note that the ideal description assumes perfect symmetries, which is not the case in the final implementation [35]. In the final construction, asymmetries result in static force imbalance. However, the BEST principle is a vast improvement compared to previous designs.

With the BEST principle, fully utilized in the B81, a better low-frequency performance than the previous B71 is achieved [25]. In essence, the prototype B81 was developed by considering three important parameters: desired stimulation frequency, output power and size. B81 solves these trade-offs in a balanced way and achieves both acceptable distortion levels and good low frequency performance, in combination with a user-friendly size. In summary, the B81 enables hearing-and balance diagnostics at lower frequencies and generates less distortion; allowing more accurate measurements [35]. With the BEST principle's verified benefits, the development proceeds even further with the B250, which is the transducer used in this study.

In 2018, the BC transducer prototype B250 was introduced by B. Håkansson et al. (Figure 2.5). Equal to the B81, the B250 is based on the BEST principle but was specifically proposed for cervical and ocular VEMP testing. Later, more or less accidentally, it was found that the B250 can be applied in ABR testing as well [7]. The B250 has a resonance frequency at 250 Hz, which is considerably lower than the resonance frequency of the B81 [6].

Figure 2.5. (Left) AA+ battery for size comparison and (Right) the transducer B250 prototype. A steel spring arrangement is attached using the small cavities on the top of the B250.

B250 dimensions:

- Diameter = 30 mm
- Height (Cylinder) = 18 mm
- Total Height = 27 mm
- Mass ~ 0.08 kg

As stated earlier, AC evoked VEMP and ABR hold drawbacks to BC counterparts. As a result, BC transducers with improved low-frequency performance are demanded within audiology. The B250 can evoke viable VEMP response at considerably lower hearing levels - approximately 30-40 dB nHL lower than in AC VEMP [6]. This enables testing without exposing patients to the harmfully loud intensity levels, that come with AC stimulation. When driven at resonance frequency of 250 Hz, the B250 outperforms the B81 in evoking viable VEMP response [6]. Consequently, the B250 may become a valuable component in modern balance diagnostics.

Additionally, it was found that ipsilateral and contralateral response using the B250 were close to identical, when operated at 250 Hz. This indicates that stimulation only needs to be applied on one mastoid in order to obtain viable cVEMP and oVEMP responses on both sides [6]. This advantage together with a compatible interface for commonly used hardware, makes up a user-friendly device. Furthermore, more accurate ABR- and VEMP testing is achieved since the B250 generates less electromagnetic radiation than the B71 and B81 [7]. However, in order to take the step from prototype to clinically applied device, further improvements are needed. In particular, further reduction of the electromagnetic radiation is prioritized which calls for investigation on how the transducer can be shielded during measurements.

2.4. The Electromagnetic Artefact

As the electrical input of the B250 varies with time, the density in magnetic flux is altered. The flux is closed not only within the transducer but also fringe into its surrounding space. When performing VEMP and ABR on human subjects, the electrodes are placed within the scope of the electromagnetic field originating from the B250. These electrodes form a loop of conductive material, through which the magnetic field lines cross. When the magnetic flux passes through this loop, an electromotive force (EMF) is induced across the wires. The induced voltage, or EMF, is described by Faraday’s law of induction.

$$\varepsilon = -A\frac{dB}{dt} = -\frac{d}{dt}(BA) \quad volt \qquad \text{(Equation 2.6)}$$

In equation 2.6, the electromotive force is denoted as **ε**, the external magnetic flux as **B** and the area enclosed by the wire loop as **A**. According to equation 2.6, the induced EMF changes with opposite polarity to the magnetic flux, as **B** fluctuates. In other words, the EMF counteracts the external magnetic field according to Lenz law. The induced voltage in the electrode wires, **ε**, might hide the recorded neurological response and is, in this context, considered an artefact.

2.5. Bobbin Coil

A short-circuit bobbin coil is designed and applied around the transducer in order to reduce the electromagnetic artefacts that occur in hearing-and balance testing, when applying BC stimuli. As described in section 2.4, the transducer gives rise to an electromagnetic field when it vibrates. In this chain of physical phenomena, a current is induced in the electrode wires that might conceal the measured neurological response. This unwanted effect is amplified as the distance between the transducer and electrodes decreases, which is the case when measurements are performed on infants and small children [7].

By enclosing the B250 with a bobbin coil, a current is induced in the coil. Subsequently, the induced current in the coil will, in itself, cause a magnetic field that counteracts the fringing magnetic field originating from the transducer. In this way, the artefact can be reduced.

A coil that can be placed near the B250 is preferred, since the electromagnetic radiation is of highest magnitude near the transducer. However, a small gap between the bobbin coil and the transducer should be reserved, to ensure that the transducer's intended function remains intact. To accomplish these requirements, a bobbin coil, tailor-made to match the proportions of the B250, was developed by Thomas Rylander and provided by the Department of Electrical Engineering (*Figure 2.6*, *Figure 2.7*). This symmetric coil is constructed by windings of insulation copper wire around a plastic cylinder; a bobbin core. As can be seen in Figure 2.6, the bobbin coil is shorted by connecting the two ends of the coil. Dimensions of the bobbin coil are presented below:

Bobbin coil

- Diameter = 85 mm
- Height = 31 mm
- Mass ~ 0.55 kg

Copper wire

- Radius = 1 mm
- Number of windings = 100
- Total wire length = 22 m

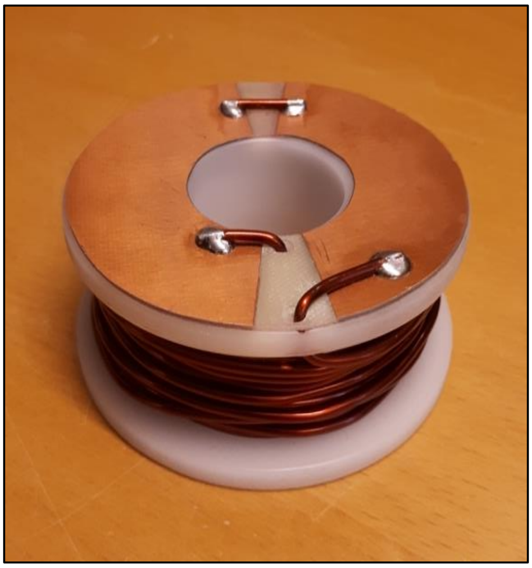

Figure 2.6. Bobbin coil.

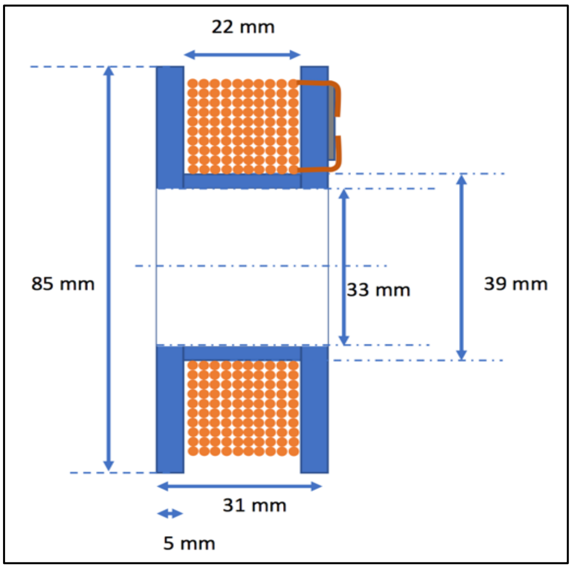

Figure 2.7. Cross-sectional view of the Bobbin coil.

3. METHOD

In this section, a detailed description of the experimental procedure is presented. A list of utilized equipment is followed by a description of the methodology applied in synthetic cVEMP, oVEMP and ABR measurements. Lastly, a short series of ABR measurements are performed on a human subject. All measurements are performed in the Hearing Research Lab that belongs to the Department of Electrical Engineering.

3.1 Equipment

- B250 transducer.
- Bobbin coil.
- Watermelon as a substitute for the human skull - “synthetic skull”.
- Eclipse EP25 signal generator, Interacoustics.
- Preamplifier, Interacoustics.
- OtoAcess software, including ASSR and EPxx modules.
- Sanibel snap electrodes.
- Nuprep skin prep gel.
- Adjustable elastic head bands.
- Plastic extension.
- Audiometric steel spring.
- Alcohol wipes.

3.2 Synthetic oVEMP

The applied synthetic oVEMP and cVEMP methodologies are mainly inspired by VEMP measurements conducted by Håkansson et al. [6]. In these measurements, VEMP testing is performed using the B250 at different frequencies and intensities. The results of this study indicate that threshold values for evoking viable VEMP responses among the participating human subjects, range from 50 to 65 dB nHL with tone bursts of 250 Hz, using the B250 [6]. Since intensity values within this range are proven to be successful in cVEMP and oVEMP testing, a decision is made to include intensity levels 55 and 65 dB nHL in the synthetic VEMP measurement series. Input frequencies of 250 Hz and 500 Hz are included in the oVEMP measurements, to examine the impact of the bobbin coil principle at different stimuli frequencies. Tone bursts of 250 and 500 Hz, consisting of five cycles (*total length 20 and 10 ms respectively)*, are used throughout the synthetic measurement series (*ABR & VEMP*). In all these measurements, a Blackman window is used in combination with the tone burst.

Throughout the synthetic measurement series, tone bursts of intensity levels 55 and 65 dB nHL are tested, using the B250 transducer. Depending on the frequency off the tone burst, a specific correction factor is added on top of the input intensity level. These correction values are specific for the B250 and have been provided by the Department of Electrical Engineering. Correction value for 250 and 500 Hz is +10 dB HL; resulting in input intensities of 65 and 75 dB nHL.

Additionally, three “subjects” are created by marking out different electrode positions for each one on the watermelon. By altering the distance between electrodes and transducer, the intention is to simulate three different head sizes, with the smallest head size in Subject 1 (S1), the medium size in Subject 2 (S2) and the largest size in Subject 3 (S3). These subjects are used in synthetic cVEMP and ABR as well.

The first step is to mark a position for the transducer placement. This transducer position is used as a reference point, from which placement markings of the electrodes are determined. The idea is to roughly simulate oVEMP with mastoid stimulation, which means that the transducer is placed just behind the visible part of the ear, on a human subject. A random spot on the watermelon is marked out with blue tape, representing an artificial ear canal. As displayed in Figure 3.1, the transducer is placed approximately 1 cm behind this spot.

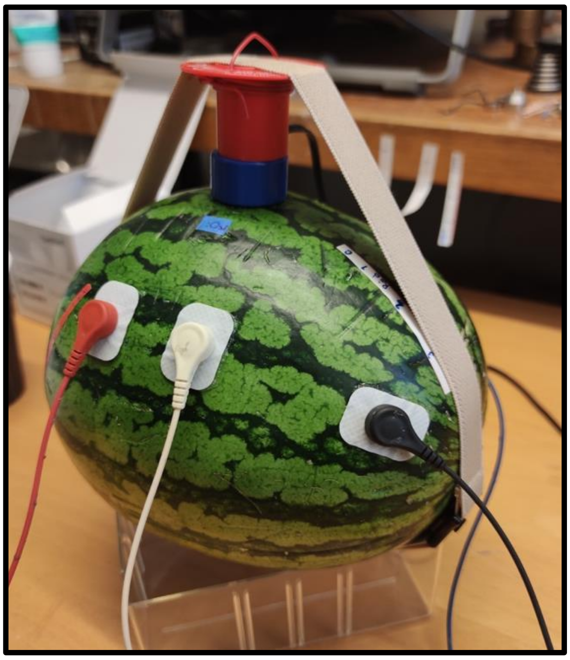

Figure 3.1. Electrode positions S1, oVEMP. The artificial head is in horizontal position, with the artificial ear canal (Marked with blue tape) facing upwards. Transducer is applied with a plastic extension on top and an elastic headband. No bobbin coil attached.

From the transducer position, bipolar electrodes (*red and white*) are placed at a distance of approximately 5 centimeters (S1), measured along the surface of the watermelon (*Figure 3.1*). The distance between the two bipolar electrodes is 2 centimeters in all three subjects. In S2, the gap between transducer and bipolar electrodes is increased by 2 centimeters, resulting in a total distance of 7 centimeters. An additional 2 centimeters is added to this distance in S3, making it 9 centimeters in total. The transducer position is fixed throughout the measurement series, including the synthetic cVEMP and ABR tests. Placement of the ground electrode (*black*) is done by roughly imitating a real oVEMP measurement, where the ground is positioned at the upper rim of sternum [6]. For S1, the ground is placed at a distance of 5 centimeters from the white electrode and 9 centimeters from the transducer (*Figure 3.1*). Ground positions are marked out for each subject, with 2 centimeters spacing between them. All though three different positions for the ground electrode may seem excessive, they come to use in cVEMP, where the same positions are used for the active electrode (*white*). Having a separate ground for each subject also means that each electrode must be detached and reattached when switching between subjects. In this way, the electrode impedances are better balanced, since the impedance tends to drop with time.

Distances between electrode markings and transducer for each subject, are presented below:

S1:
- Ground to White ≈ 5 cm
- Ground to Transducer ≈ 9 cm
- Red to White ≈ 2 cm
- Bipolar electrodes to Transducer ≈ 5 cm

S2:
- Ground to White ≈ 5. 5 cm
- Ground to Transducer ≈ 11 cm
- Red to White ≈ 2 cm
- Bipolar electrodes to Transducer ≈ 7 cm

S3:
- Ground to White ≈ 6 cm
- Ground to Transducer ≈ 13 cm
- Red to White ≈ 2 cm
- Bipolar to electrodes - Transducer ≈ 9 cm.

For the electrical impedance between the electrodes to match, all electrodes need to be attached when performing VEMP using the Interacoustics hardware and OtoAccess software. Therefore, the blue electrode that does not serve any purpose in the tests is connected on the backside of the watermelon (*Figure 3.2*), to enable the recordings.

To obtain a feasible recorded signal, it is important to establish acceptable contact between the snap electrodes and the watermelon. The surface of the watermelon, where the snap electrodes are to be attached, is therefore prepared by thoroughly cleansing it using the Nuprep gel and cotton pads. Once the electrodes are attached, the impedance is checked using the preamplifier. The impedance for each electrode should preferably be below 3 kΩ. If this requirement is not met, the cleaning procedure is repeated. The impedance is checked prior to the recordings without the bobbin coil as well as before the following recordings, where the coil is attached. In every subject switch, the snap electrodes are exchanged for a set of unused ones. The highest measured impedance is noted in Tables 4.1 – 4.3, along with measured signal amplitudes. Artefact amplitudes in each test is determined by finding the maximum distance between two consecutive peaks.

The contact between the B250 and the watermelon as well as the pressure applied to it, are factors that need to be considered [6]. To maintain a relatively equal pressure and contact throughout the measurements, a plastic extension is placed on top of the transducer to keep the bobbin coil from interfering with the elastic head band arrangement (*Figure 3.2*, *Figure 3.3*). The pressure applied to the B250 is measured in experiments with and without the bobbin coil attached using a mechanical spring scale, to ensure a constant pressure of approximately 10 N.

Figure 3.2. S1, synthetic oVEMP. bobbin coil attached.

Figure 3.3. Plastic extension with a small opening for wires.

Before the synthetic oVEMP measurements commence, an initial test is carried out to determine the impact of various external factors on the recordings. The configuration in Figure 3.1 is used in these measurements. Included factors are lighting/ventilation fan and twinning of electrode wires. The light switch in the laboratory room also controls the ventilation fan, which means that these two factors are considered as one. An additional factor that is included in the initial test, is radio sound coming from another laboratory setup that runs uninterruptedly. This is part of a different experiment being carried out in the laboratory room that should preferably not be disrupted. To examine whether the radio sound affects the recordings, this system is turned off for a few minutes.

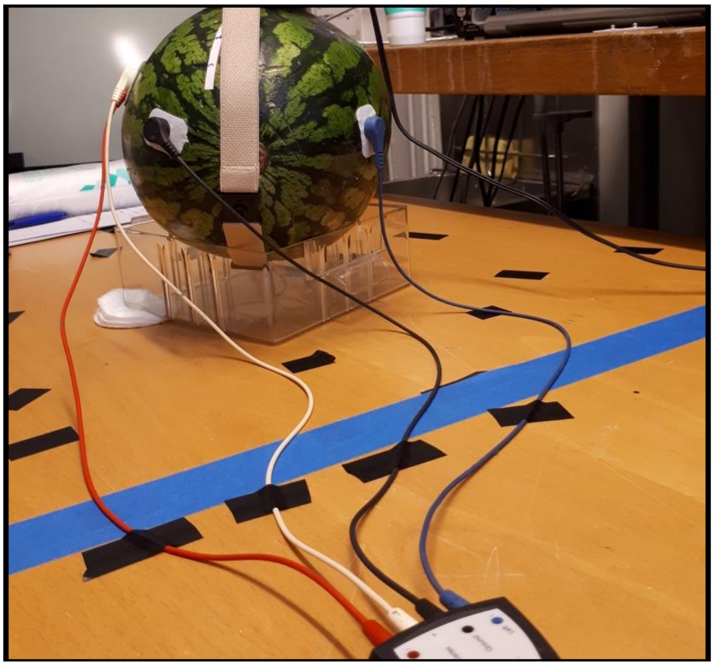

Figure 3.4. Separation of the electrode wires using tape.

The only factor that proved to have significant impact on the recordings, was twinned electrode wires. Therefore, the wires are taped to the table and kept separated to the fullest extent possible, in order to minimize the effect of alternating factors throughout the measurements (*Figure 3.4*). However, the wire layout is inevitably changed when switching subject, which affects the area of the wire loop (Equation 2.6).

Two frequencies, two intensity levels and three artificial subjects are tested with and without the bobbin coil attached. A total of 24 tests are included in the synthetic oVEMP measurements series, eight tests for each subject. For each subject, the measurement series begins with four test configurations without the bobbin coil, followed by the same four configurations with the bobbin coil attached. Input parameters and measured results are presented in Tables 4.1 – 4.3. Intensity levels and frequencies are altered in the protocol displayed in Figure 3.5. All other settings displayed in Figure 3.5 remains throughout the synthetic oVEMP tests. All stimulus is applied “ipsilaterally” relative to the electrodes.

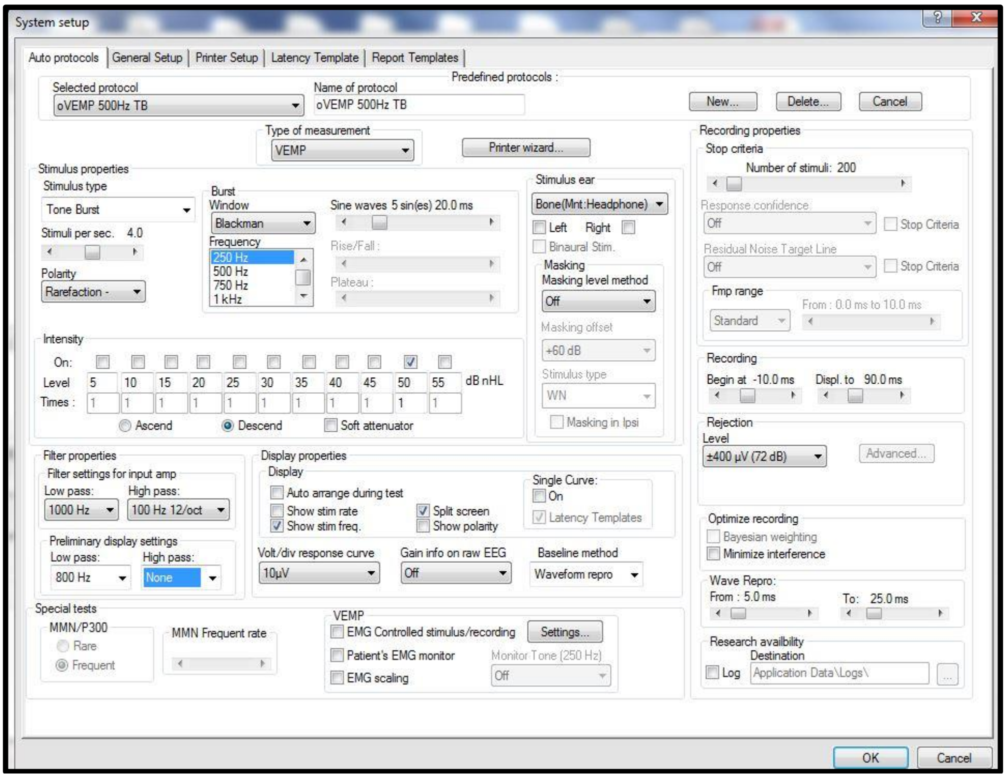

Figure 3.5. Settings OtoAccess EPXX module, synthetic oVEMP recordings. Frequency and intensity levels are altered in the protocol.

3.3 Synthetic cVEMP

The synthetic cVEMP procedure is an attempt to imitate real cVEMP measurements with mastoid stimuli. On a human subject, the cVEMP response is measured over the sternocleidomastoideus (*SCM*) muscle, with the reference electrode placed at the upper rim of sternum [6] and the ground placed on a bony part of the skull, for instance, on the lower forehead. This is roughly imitated by marking out an artificial SCM muscle, on which three different electrode positions are measured out; one for each artificial subject. In S1, this electrode marking is at a distance of 5 centimeters from the transducer, with an increasing distance of 2 centimeters per subject. The ground markings from the oVEMP measurements, are in cVEMP used as positions for the reference electrode (*white*). Distance between bipolar electrodes is approximately 3,5 centimeters in all subjects.

Figure 3.6. Electrode placement in synthetic cVEMP, S1. The artificial head is in horizontal position. Red bipolar electrode placed on the artificial SCM muscle, ground electrode on the virtual forehead.

As in synthetic oVEMP, three different ground positions are measured out. Ground electrode positions are marked at distances of 7, 9 and 11 centimeters from the transducer, where the location of the lower forehead is approximately estimated to be (*Figure 3.6*). The blue electrode is randomly attached to the backside of the watermelon; however, it does not serve any purpose in the recordings. Distances measured between electrodes and transducer for each subject are presented below:

S1:

- Red to Ground ≈ 11 cm
- Ground to Transducer ≈ 7 cm
- Red to Transducer ≈ 5 cm
- White to Transducer ≈ 9 cm
- White to Ground ≈ 11,5 cm

S2:

- Red to Ground ≈ 13,5 cm
- Ground to Transducer ≈ 9 cm
- Red to Transducer ≈ 7 cm
- White to Transducer ≈ 11 cm
- White to Ground ≈ 13 cm

S3:

- Red to Ground ≈ 15,5 cm
- Ground to Transducer ≈ 11 cm
- Red to Transducer ≈ 9 cm
- White to Transducer ≈ 13 cm
- White to Ground ≈ 13 cm

Synthetic cVEMP is performed using the same input parameters as in oVEMP. The only difference compared to synthetic oVEMP, is the placement of the electrodes. Two intensity levels (65 & 75 dB nHL), two frequencies (250 & 500 Hz) and three subjects are tested with and without the bobbin coil attached; resulting in 24 measurements in total. Just as in oVEMP, the surfaces are thoroughly cleansed before attaching the snap electrodes. The pressure between transducer and watermelon is verified using the mechanical spring scale. Protocol settings used throughout the cVEMP measurement series are displayed in Figure 3.7. Frequencies and intensity levels are altered, depending on the current configuration of the test. Results and input parameters are presented in Table 4.4 – 4.6.

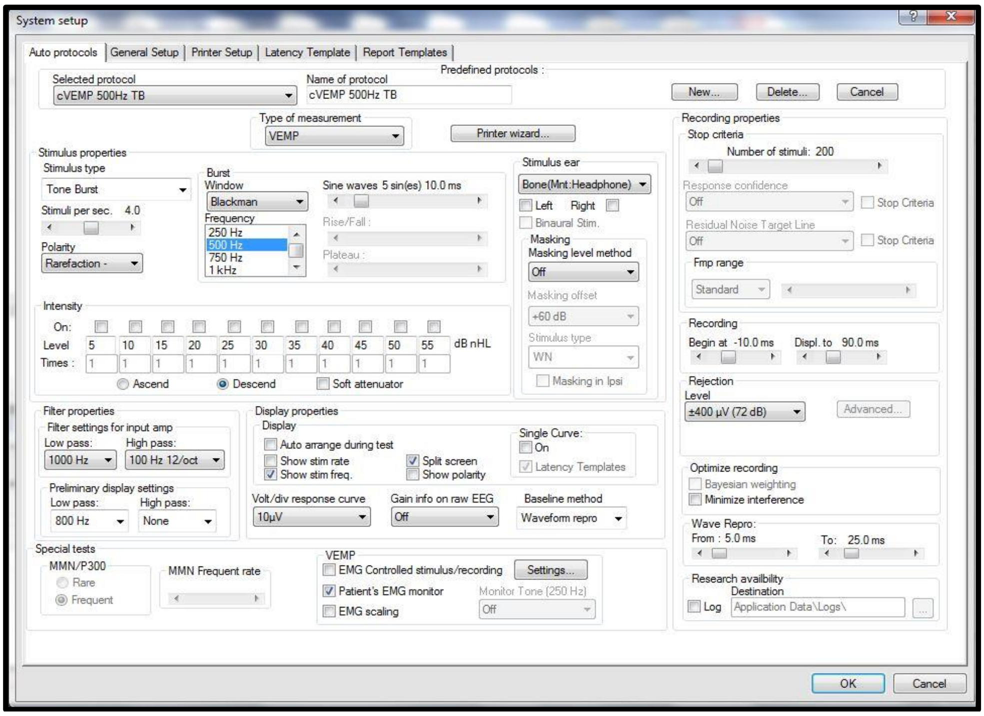

Figure 3.7. Protocol settings OtoAccess EPXX, synthetic cVEMP.

3.4 Synthetic ABR

The procedure in synthetic ABR is very similar to the VEMP methodologies. What differs between the three synthetic procedures is mainly the placement of the electrodes relative to the transducer. Similar to the synthetic VEMP measurements, the synthetic ABR procedure is an attempt to simulate real ABR. This procedure is mainly inspired by the ABR methodology described in the Eclipse EP25 manual [26]. On a human subject, the ground electrode is placed on the lower forehead. Therefore, the same ground markings that were used in synthetic cVEMP, can be used in synthetic ABR as well. Bipolar electrodes are placed: one on the high forehead (*white*) and one on the mastoid (*red*). The electrode markings intended for the inverting electrode (*red*) in synthetic cVEMP, are used in the same purpose in these measurments. White bipolar electrode positions are marked at a distance of approximately 10, 12 and 14 centimeters from the transducer position. The distance between white electrode and ground is approximately 3,5 centimeters in all subjects. As in synthetic VEMP, the electrode markings that are closest to the transducer, are intended for S1.

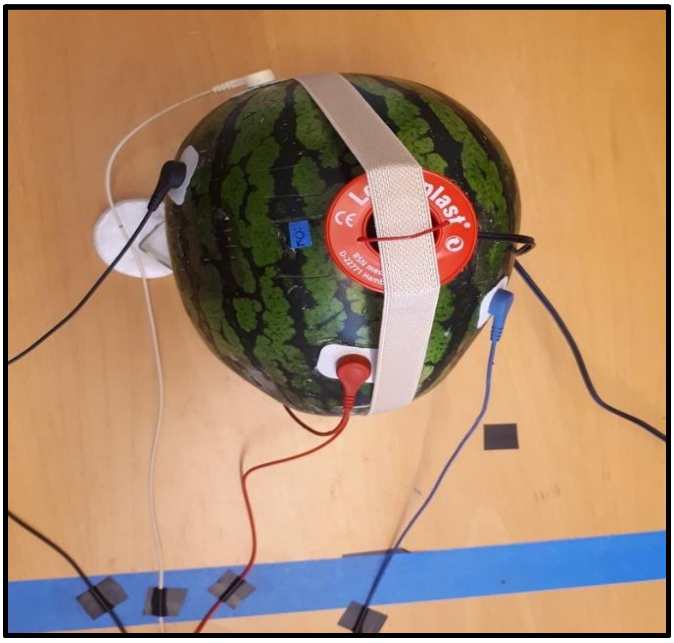

Figure 3.8. Electrode placement synthetic ABR, S1.
Artificial head in horizontal position (From above).
Red bipolar electrode on the synthetic mastoid.
White bipolar electrode is placed approximately
3.5 centimeters from the ground electrode.

In real ABR, red and blue electrodes can be used in combination to measure neurological response on both sides simultanously. The ABR artefact increases when the electrodes must be placed close to the transducer [7]. Therefore, it is more relevant to measure on the ispsilateral side, i.e. the left side of the artificial head, rather than the right side (*contralateral*). As in synthetic VEMP, the blue electrode is placed randomly on the backside of the watermelon but remains unused throughout the synthetic ABR tests. All measured distances between electrode postions and transducer are presented om the following page:

S1:

- Red to Ground ≈ 11 cm
- Ground to Transducer ≈ 7 cm
- Red to Transducer ≈ 5 cm
- White to Transducer ≈ 10 cm
- White to Ground ≈ 3,5 cm
- Red to White ≈ 15 cm

S2:

- Red to Ground ≈ 13.5 cm
- Ground to Transducer ≈ 9 cm
- Red to Transducer ≈ 7 cm
- White to Transducer ≈ 12 cm
- White to Ground ≈ 3,6 cm
- Red to White ≈ 19 cm

S3:

- Red to Ground ≈ 15.5 cm
- Ground to Transducer ≈ 11 cm
- Red to Transducer ≈ 9 cm
- White to Transducer ≈ 14 cm
- White to Ground ≈ 3,3 cm
- Red to White ≈ 21 cm

In synthetic ABR measurements, tone bursts of frequencies 250 and 500 Hz are included. Unlike the synthetic VEMP tests, intensity levels 30, 40 and 50 dB nHL (*displayed values in OtoAccess: 20, 30, 40 dB nHL respectively*), are tested in synthetic ABR. The number of averages is increased to 1000, and the stimuli rate is increased to 22.1 stim/sec. Same procedures regarding subject switching and pressure continuity, as in synthetic VEMP, are applied in synthetic ABR. Three artificial subjects, three intensities and two frequencies are tested with and without the Bobbin coil attached; resulting in 36 tests in total. For each subject, the measurement series begins with 6 test configurations without the Bobbin coil, followed by the same 6 configurations with the Bobbin coil attached. Input parameters and results are presented in Tables 4.7 – 4.9.

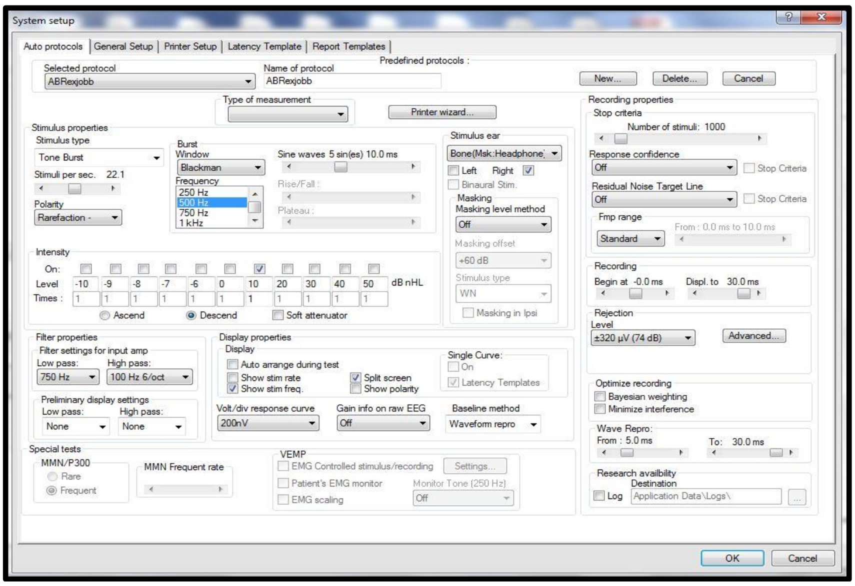

Figure 3.9. Protocol settings in synthetic ABR. Intensity levels and frequencies are altered depending on the current configuration of the test.

3.5 ABR (Human subject)

Lastly, a sequence of real ABR measurements is performed on a human subject. The intention here is not to execute a complete ABR investigation, including threshold evaluation on each relevant frequency octave. Instead, a short series of measurements focusing primarily on frequencies: 250 Hz, 500 Hz and 1 kHz, is carried out. The idea is to find intensity levels that provide responses similar to the expected ABR waveform; primarily to distinguish the wave V component, while also providing a distinct electromagnetic artefact. Artefacts are desired in these measurements, since the aim is to compare the artefact amplitudes in different test configurations. At the chosen intensity levels, with associated frequency and stimuli waveform, tests are carried out with and without the bobbin coil attached in order to evaluate its functionality in practice. Two commonly used stimuli waveforms are applied: tone bursts and chirps. At stimuli frequencies 500 Hz and 1000 Hz, NB LS CE-Chirps® are used. However, these chirps are not available in the OtoAccess software for 250 Hz stimuli. In order to include 250 Hz in the measurement series, tone bursts are used instead. These tone bursts consist of three periods (1:1:1); resulting in a total signal duration of 12 milliseconds. The same correction factor as in the synthetic tests, is added on top of the intensity level used for the 250 Hz tone burst (10 dB HL). However, when using a chirp, the correction value is equal to zero.

In order to obtain low electrode impedances, the skin surface is thoroughly cleansed prior to electrode attachment, using the Nuprep gel and alcohol wipes. An electrode impedance below 3 kΩ is verified using the preamplifier, prior to the tests with and without the bobbin coil attached. Electrodes are attached to the human subject according to the ABR guide described in the Eclipse manual [26]:

- **Red inverting electrode:** right mastoid.
- **Blue inverting electrode:** left mastoid.
- **Active electrode (*White*):** high forehead.
- **Ground (Black*)*:** lower forehead, a few centimeters below the active electrode.

It should be noted that the blue electrode serves no purpose in these recordings. All ABR recordings are done ipsilaterally. Equal to the previous synthetic measurements, it must however be attached.

In measurements with no bobbin coil attached, the B250 is placed on the right mastoid using an audiometric steel spring arrangement (*Figure 3.10*). The steel spring is, however, not appropriate for tests in which the bobbin coil is attached. Partly because of its inability to carry the mass of the bobbin coil, but also because of the height difference between the attachment point on the B250 and the bobbin coil. The attachment point of the steel spring, on the B250, is at a height of approximately 27 millimeters while the height of the bobbin coil is 31 millimeters. This difference in height obstructs the steel spring arrangement from reaching down to the mastoid, through the bobbin coil. To solve this problem, the transducer is firmly attached using two elastic headbands (*Figure 3.11*). The plastic extension used in the synthetic procedures (*Figure 3.3*), is placed between the blue headband and the transducer to ensure steady contact between the B250 and the mastoid. After the tests without the bobbin coil attached, a circle is drawn around the B250 with a marker. This marking is later used when positioning the transducer along with the bobbin coil, prior to the following measurements.

Figure 3.10. Electrode placement, ABR on human subject. Steel spring arrangement keeps the transducer firmly positioned on the mastoid. No bobbin coil attached.

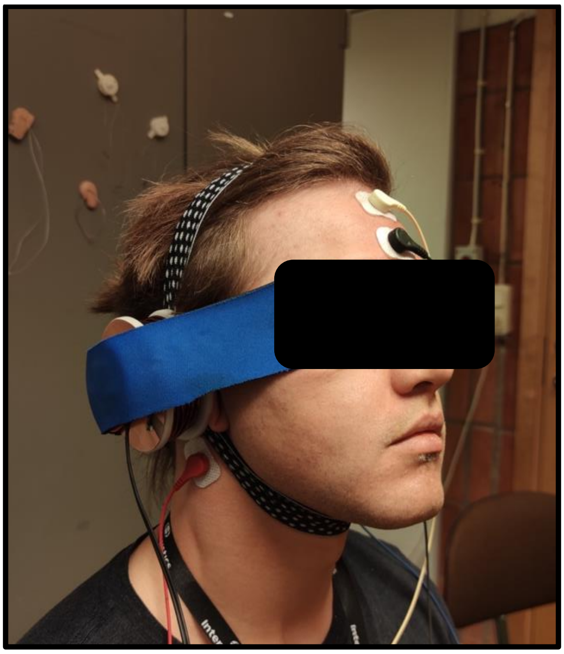

Figure 3.11. Electrode placement, ABR on human subject. Bobbin coil and transducer attached using two elastic headbands.

Three iterations on three frequencies are tested with and without the bobbin coil attached; resulting in 18 measurements in total. All stimuli configurations are first tested without the bobbin coil, followed by the same tests with the bobbin coil attached. Frequencies of 500 Hz and 1000 Hz are tested using the NB LS CE-Chirp®, while tone bursts are used at 250 Hz. Results and waveforms obtained from the real ABR tests are presented in Table 4.10 and Figure 4.9 - 4.14, respectively.

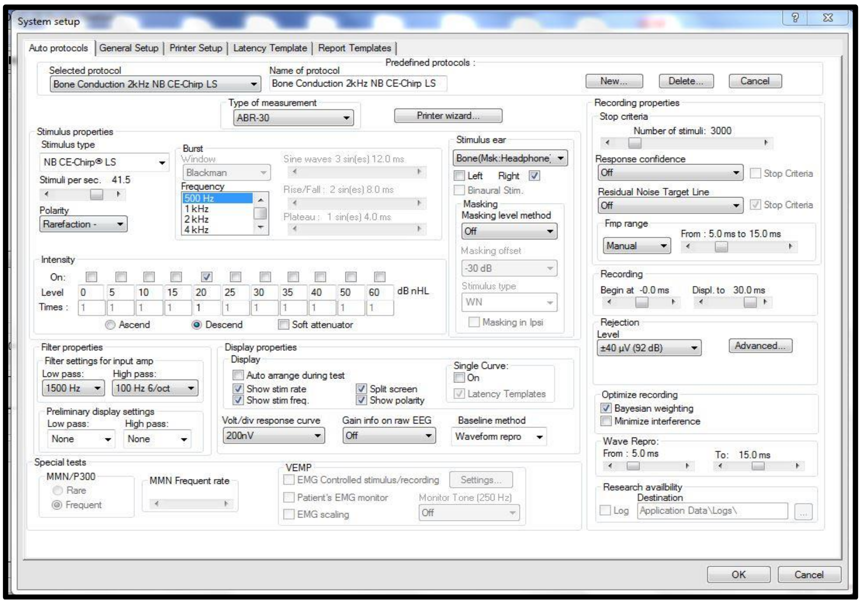

Figure 3.12. Settings OtoAccess, ABR on human subject. Stimulus type and frequencies are altered depending on the current test configuration. All other settings remain throughout the ABR measurements.

4. RESULTS

This section includes complete tables of all measurements performed, including figures displaying the reduction of electromagnetic artefacts, among the three artificial subjects.

4.1 Synthetic oVEMP

Results obtained in the synthetic oVEMP measurements are presented in the following sub-section.

Tables 4.1, 4.2, 4.3 – Electromagnetic artefact measured with the bobbin coil removed (Off) and attached (On) in synthetic oVEMP. The number of recorded stimuli in all measurements is 200.

S1 - oVEMP

Index	Impedance [Ohm]	Intensity [dB nHL]	Frequency [Hz]	Bobbin coil	Artefact Amp. [µVolt]	Reduction
1	1000	65	250	Off	37,33	
2	900	65	250	On	13,05	
						65.04%
3	1000	75	250	Off	96,95	
4	900	75	250	On	33,345	
						65.61%
5	1000	65	500	Off	33,03	
6	900	65	500	On	13,56	
						58.94%
7	1000	75	500	Off	99,2	
8	900	75	500	On	43,03	
						56.62%

S2 - oVEMP

Index	Impedance [Ohm]	Intensity [dB nHL]	Frequency [Hz]	Bobbin coil	Artefact Amp. [µVolt]	Reduction
9	750	65	250	Off	31,76	
10	750	65	250	On	13,76	
						56.68%
11	750	75	250	Off	79,63	
12	750	75	250	On	34,48	
						56.7%
13	750	65	500	Off	28,37	
14	750	65	500	On	15,40	
						45,71%
15	750	75	500	Off	85,25	
16	750	75	500	On	51,125	
						40,03%

S3 - oVEMP

Index	Impedance [Ohm]	Intensity [dB nHL]	Frequency [Hz]	Bobbin coil	Artefact Amp. [μVolt]	Reduction
17	1400	65	250	Off	30,52	
18	1200	65	250	On	4,9845	
						83.67%
19	1400	75	250	Off	79,745	
20	1200	75	250	On	14,465	
						81.86%
21	1400	65	500	Off	16,155	
22	1200	65	500	On	12,37	
						23.43%
23	1400	75	500	Off	49,91	
24	1200	75	500	On	40,045	
						19,77%

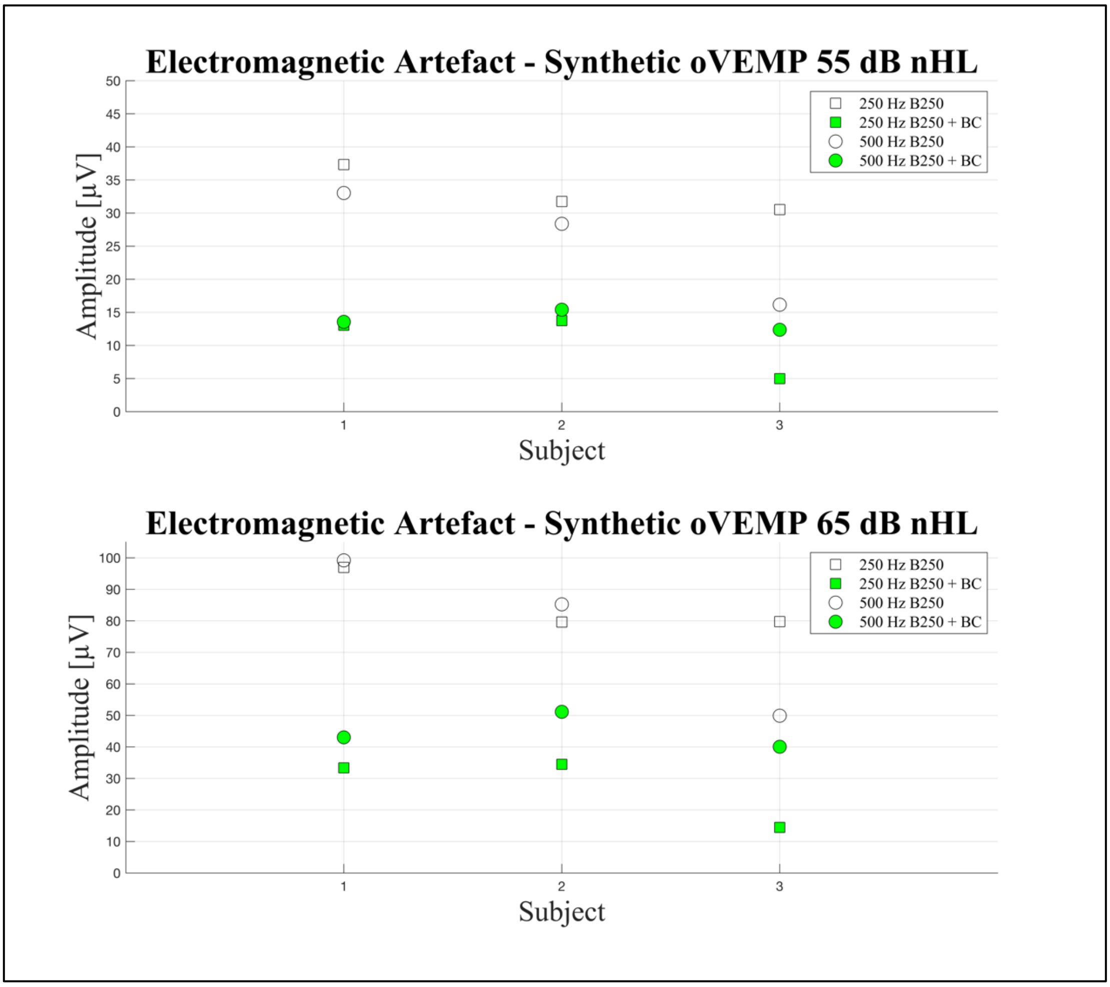

*Figure 4.1. Comparison of the electromagnetic artefact with the bobbin coil (BC) removed (blank) and attached (green) to the B250 transducer in synthetic oVEMP. The comparison is shown at two frequencies (250 & 500 Hz). Corrected intensities are **65** and **75** dB nHL.*

4.2 Synthetic cVEMP

Results from synthetic cVEMP measurements are presented in tables 4.4, 4.5 and 4.6.

Tables 4.4, 4.5, 4.6 – Electromagnetic Artefact measured with the bobbin coil removed (Off) and attached (On) in synthetic cVEMP. The number of recorded stimuli in all measurements is 200.

S1 - cVEMP

Index	**Impedance [Ohm]**	**Intensity [dB nHL]**	**Frequency [Hz]**	**Bobbin coil**	**Artefact Amp. [µVolt]**	**Reduction**
1	1300	65	250	Off	36,245	
2	1300	65	250	On	20,53	
						43,35%
3	1300	75	250	Off	85,47	
4	1300	75	250	On	54,945	
						35,71%
5	1300	65	500	Off	23,675	
6	1300	65	500	On	19,515	
						17,57%
7	1300	75	500	Off	71,58	
8	1300	75	500	On	64,77	
						9,51%

S2 - cVEMP

Index	**Impedance [Ohm]**	**Intensity [dB nHL]**	**Frequency [Hz]**	**Bobbin coil**	**Artefact Amp. [µVolt]**	**Reduction**
9	1000	65	250	Off	23,675	
10	1000	65	250	On	5,7935	
						75,53%
11	1000	75	250	Off	57,205	
12	1000	75	250	On	22,605	
						60,48%
13	1000	65	500	Off	26,76	
14	1000	65	500	On	14,205	
						46,91%
15	1000	75	500	Off	77,25	
16	1000	75	500	On	50,46	
						34,68%

S3 - cVEMP

Index	Impedance [Ohm]	Intensity [dB nHL]	Frequency [Hz]	Bobbin coil	Artefact Amp. [μVolt]	Reduction
17	1000	65	250	Off	32,98	
18	1000	65	250	On	6,101	
						81,50%
19	1000	75	250	Off	81,525	
20	1000	75	250	On	25,37	
						68,88%
21	1000	65	500	Off	25,395	
22	1200	65	500	On	11,42	
						55,03%
23	1000	75	500	Off	77,18	
24	1000	75	500	On	39,765	
						48,48%

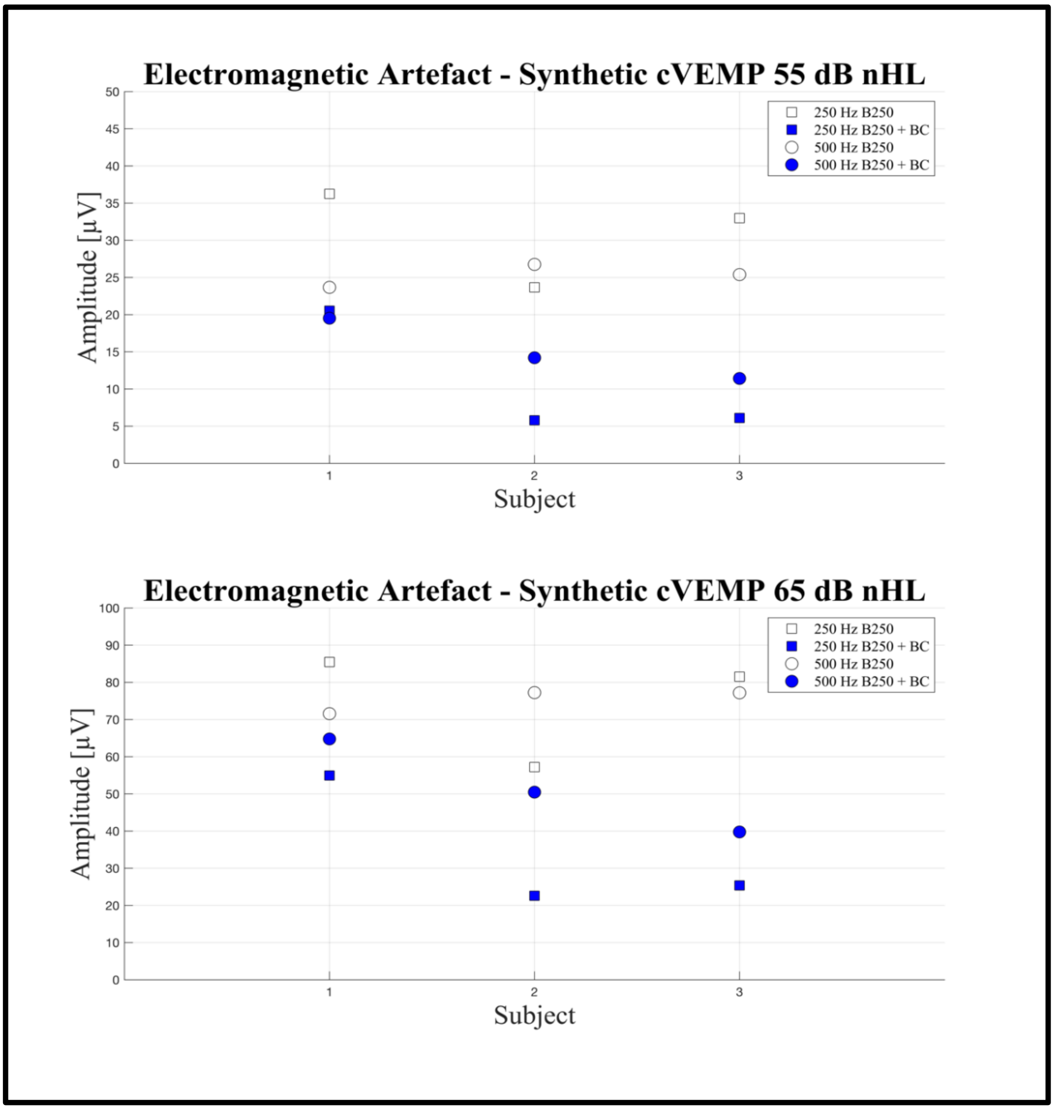

*Figure 4.2. Comparison of the electromagnetic artefact with the bobbin coil (BC) removed (blank) and attached (blue) to the B250 transducer in synthetic cVEMP. The comparison is shown at two frequencies (250 & 500 Hz). Corrected intensities are **65** and **75** dB nHL.*

4.3 Synthetic ABR

Results from synthetic ABR measurements are presented in the following sub-section

Table 4.7, 4.8, 4.9 – Electromagnetic Artefact measured with the bobbin coil removed (Off) and attached (On). Recorded stimuli is 1000 for each measurement. Waveforms that are hard to distinguish are marked with an asterisk (*). Note: Impedance displayed within parentheses shows the smallest measured value.

S1 – ABR

Index	Impedance [Ohm]	Intensity [dB nHL]	Frequency [Hz]	Bobbin coil	Artefact Amp. [nVolt]	Reduction
1	1700 (<500)	30	250	Off	261	
2	1900 (500)	30	250	On	50*	
						80,84%
3	1700 (<500)	40	250	Off	845	
4	1900 (500)	40	250	On	133	
						84,26%
5	1700 (<500)	50	250	Off	2668	
6	1900 (500)	50	250	On	503	
						81,14%
7	1700 (<500)	30	500	Off	123	
8	1900 (500)	30	500	On	30*	
						75,61%
9	1700 (<500)	40	500	Off	385	
10	1900 (500)	40	500	On	79	
						79,48%
11	1700 (<500)	50	500	Off	1279	
12	1900 (500)	50	500	On	267	
						79,12%

S2 - ABR

Index	**Impedance [Ohm]**	**Intensity [dB nHL]**	**Frequency [Hz]**	**Bobbin coil**	**Artefact Amp. [nVolt]**	**Reduction**
13	1600 (600)	30	250	Off	215	
14	1300 (600)	30	250	On	14*	
						93,49%
15	1600 (600)	40	250	Off	626	
16	1300 (600)	40	250	On	124	
						80,19%
17	1600 (600)	50	250	Off	2193	
18	1300 (600)	50	250	On	439	
						79,98%
19	1600 (600)	30	500	Off	114	
20	1300 (600)	30	500	On	45	
						60,52%
21	1600 (600)	40	500	Off	351	
22	1300 (600)	40	500	On	168	
						52,13%
23	1600 (600)	50	500	Off	1244	
24	1300 (600)	50	500	On	484	
						61,09%

S3 - ABR

Index	Impedance [Ohm]	Intensity [dB nHL]	Frequency [Hz]	Bobbin coil	Artefact Amp. [nVolt]	Reduction
25	1200 (500)	30	250	Off	153	
26	1100 (500)	30	250	On	34*	
						77.78%
27	1200 (500)	40	250	Off	483	
28	1100 (500)	40	250	On	104*	
						78.4%
29	1200 (500)	50	250	Off	1615	
30	1100 (500)	50	250	On	380	
						76.47%
31	1200 (500)	30	500	Off	99	
32	1100 (500)	30	500	On	44*	
						55.56%
33	1200 (500)	40	500	Off	282	
34	1100 (500)	40	500	On	113	
						59.93%
35	1200 (500)	50	500	Off	870	
36	1100 (500)	50	500	On	371	
						57.36%

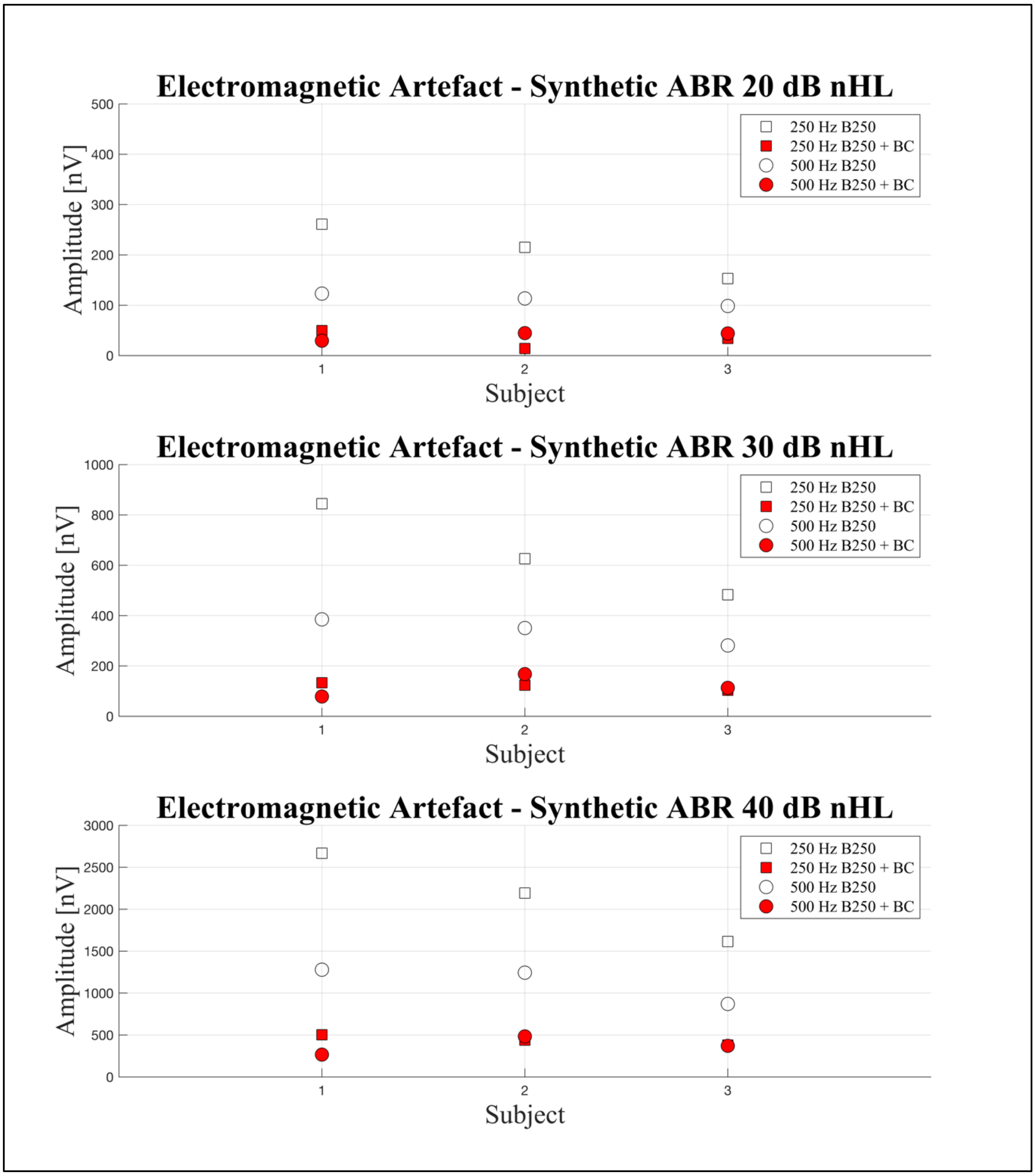

Figure 4.3. Comparison of the electromagnetic artefact with the bobbin coil (BC) removed (blank) and attached (red) to the B250 transducer in synthetic ABR. The comparison is shown at two frequencies (250 & 500 Hz). Corrected intensities are ***30***, ***40*** *and* ***50*** *dB nHL.*

4.4 ABR (Human subject)

Apart from results obtained in synthetic tests, this section presents results from human ABR measurements. This subsection includes a complete list of measurements, as well as waveforms obtained with the bobbin coil removed and attached: one for each test configuration.

Table 4.10 – Electromagnetic artefact measured with the bobbin coil removed (Off) and attached (On) in human ABR. Recorded stimuli is between 3000-4000 for each measurement. Stimuli rate of 41,5 Stimuli/Sec. 3 cycles per tone burst. n/a means that an amplitude, reduction or latency could not be determined from the graphs.

Human subject – ABR

Index	Stimulus type	Impedance [Ohm]	Intensity [dB nHL]	Frequency [Hz]	Bobbin coil	Wave V [ms]	Artefact Amp. [nVolt]	Reduction
1	Tone burst	600	40	250	Off	15,1	450	
2	Tone burst	600	40	250	On	14,5	215	
								52,22 %
3	Tone burst	600	40	250	Off	n/a	640	
4	Tone burst	600	40	250	On	n/a	260	
								59.2%
5	Tone burst	600	40	250	Off	n/a	n/a	
6	Tone burst	600	40	250	On	n/a	n/a	
								n/a
7	NB CE-Chirp	600	20	500	Off	7,27	325	
8	NB CE-Chirp	600	20	500	On	n/a	n/a	
								n/a
9	NB CE-Chirp	600	20	500	Off	8,4	210	
10	NB CE-Chirp	600	20	500	On	7,8	n/a	
								n/a
11	NB CE-Chirp	600	20	500	Off	6,33	n/a	
12	NB CE-Chirp	600	20	500	On	n/a	n/a	
								n/a

13	NB CE-Chirp	600	30	1000	Off	7,4	255	
14	NB CE-Chirp	600	30	1000	On	n/a	130	
								49,02%
15	NB CE-Chirp	600	30	1000	Off	7,4	298	
16	NB CE-Chirp	600	30	1000	On	7,2	116	
								61,01 %
17	NB CE-Chirp	600	30	1000	Off	7,53	228	
18	NB CE-Chirp	600	30	1000	On	n/a	120	
								47,25 %

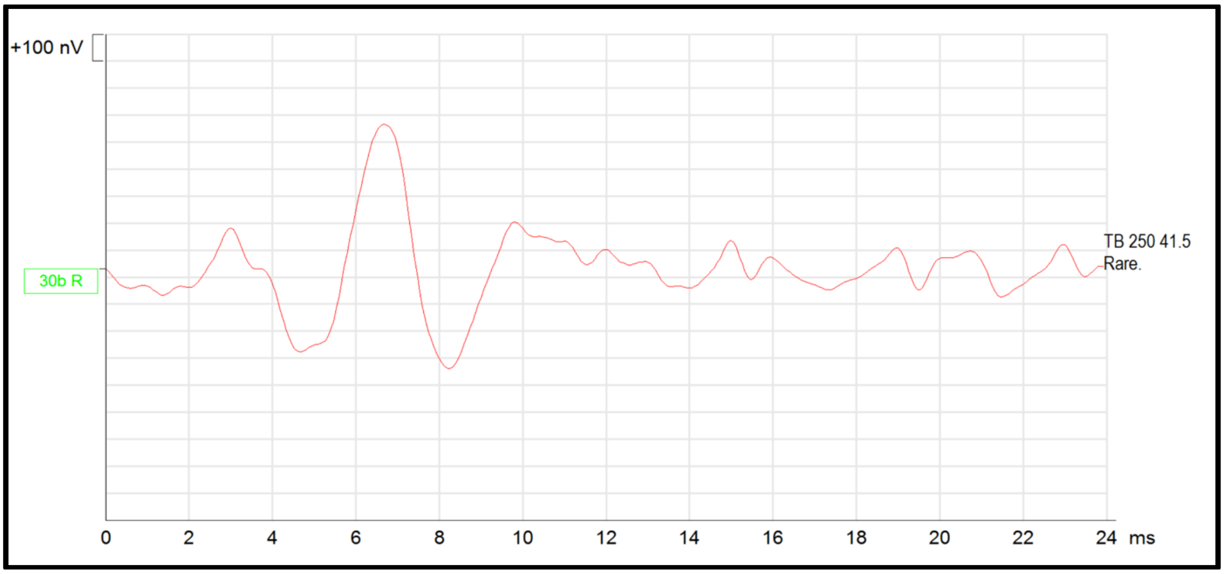

Figure 4.4. ABR-recording with the bobbin coil removed from the B250 transducer. The artefact is distinguishable in the interval 4-10 ms, with period of approx. 4 ms. Settings chosen are tone burst with 250 Hz and (corrected) intensity level 40 dB nHL (Table 4.10, Index 1).

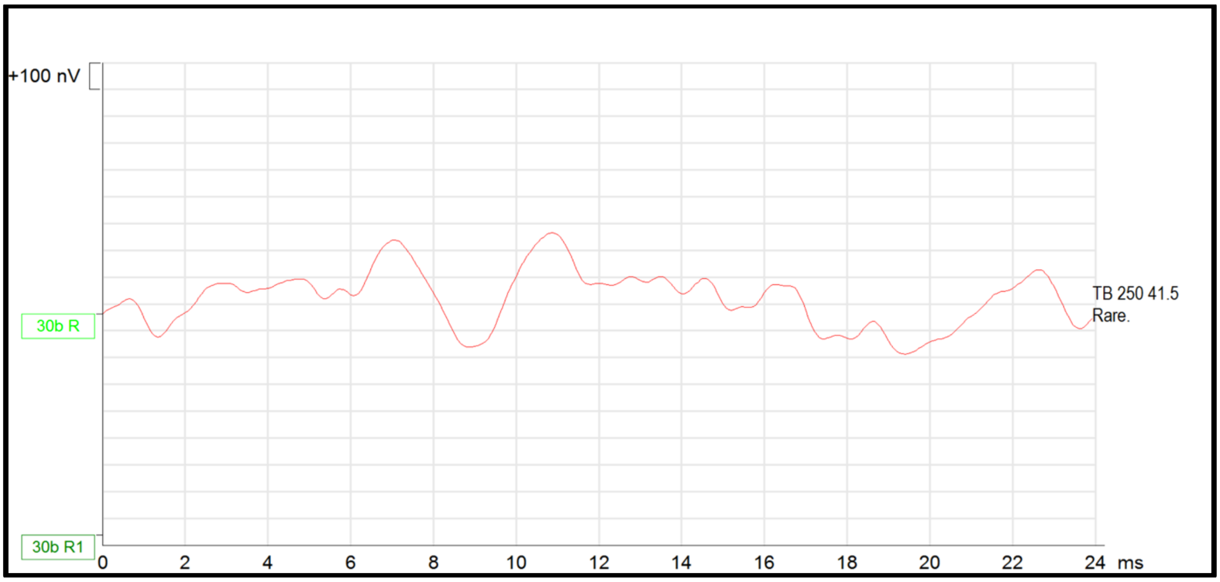

Figure 4.5. ABR-recording with the bobbin coil attached to the B250 transducer. The artefact is distinguishable in the interval 7-11 ms with period of approx. 4 ms. Settings chosen are tone burst with 250 Hz and (corrected) intensity level 40 dB nHL (Table 4.10, Index 2).

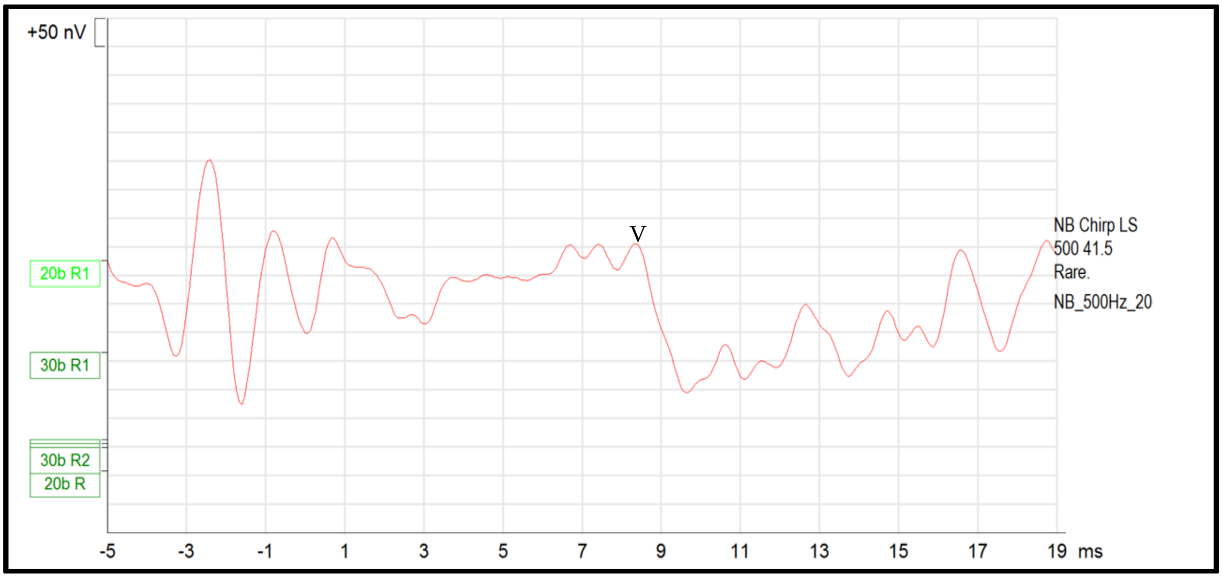

Figure 4.6. ABR-recording with the bobbin coil removed from the B250 transducer. The artefact is distinguishable in the interval (-4) to 1 ms. Wave V is observed at approximately 8,4 ms. Settings chosen are NB CE-chirp with 500 Hz and 20 dB nHL (Table 4.10, Index 9).

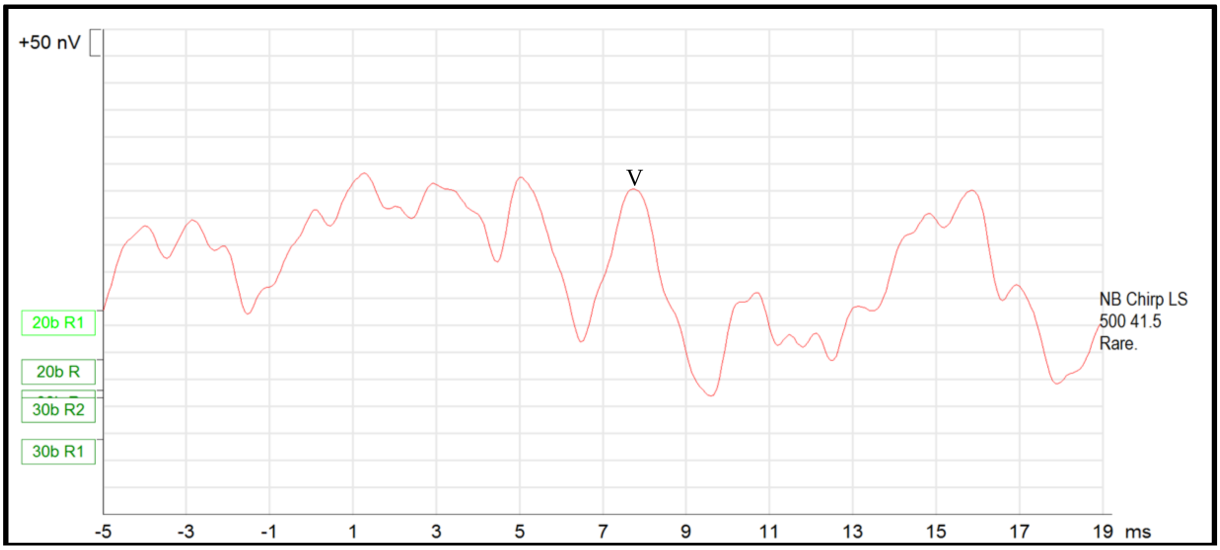

Figure 4.7. ABR-recording with the bobbin coil attached to the B250 transducer. The artefact is indistinguishable. Wave V is observed at approximately 7,8 ms. Settings chosen are NB CE-chirp with 500 Hz and 20 dB nHL (Table 4.10, Index 10).

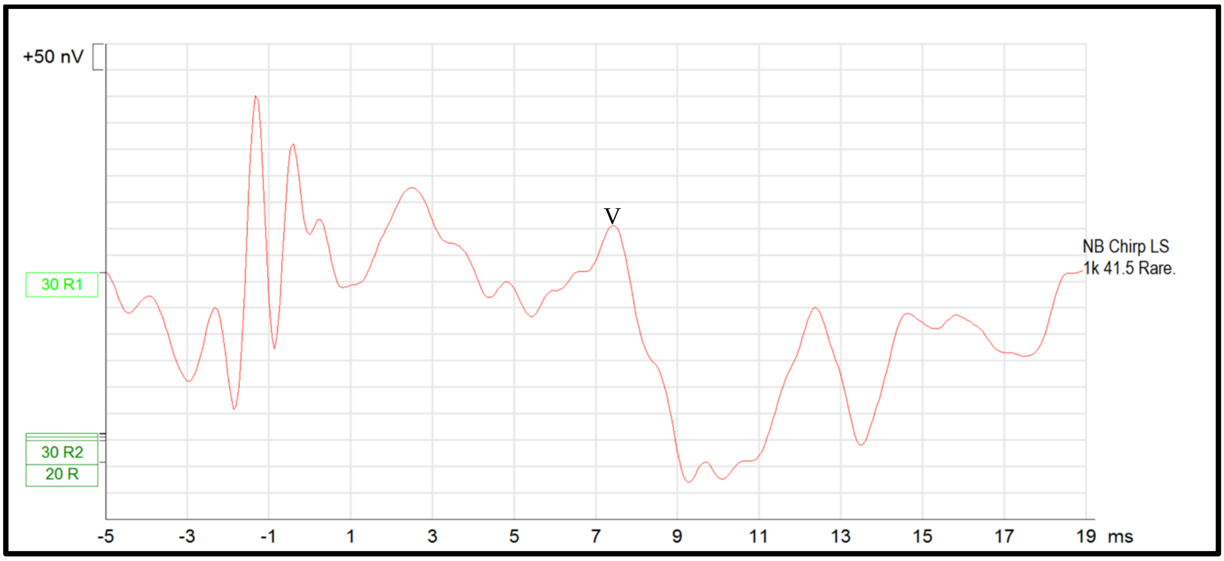

Figure 4.8. ABR-recording with the bobbin coil removed from the B250 transducer. The artefact is distinguishable in the interval (-3) to 1 ms. Wave V is observed at approximately 7,4 ms. Settings chosen are NB CE-chirp with 1000 Hz, 30 dB nHL (Table 4.10, Index 15).

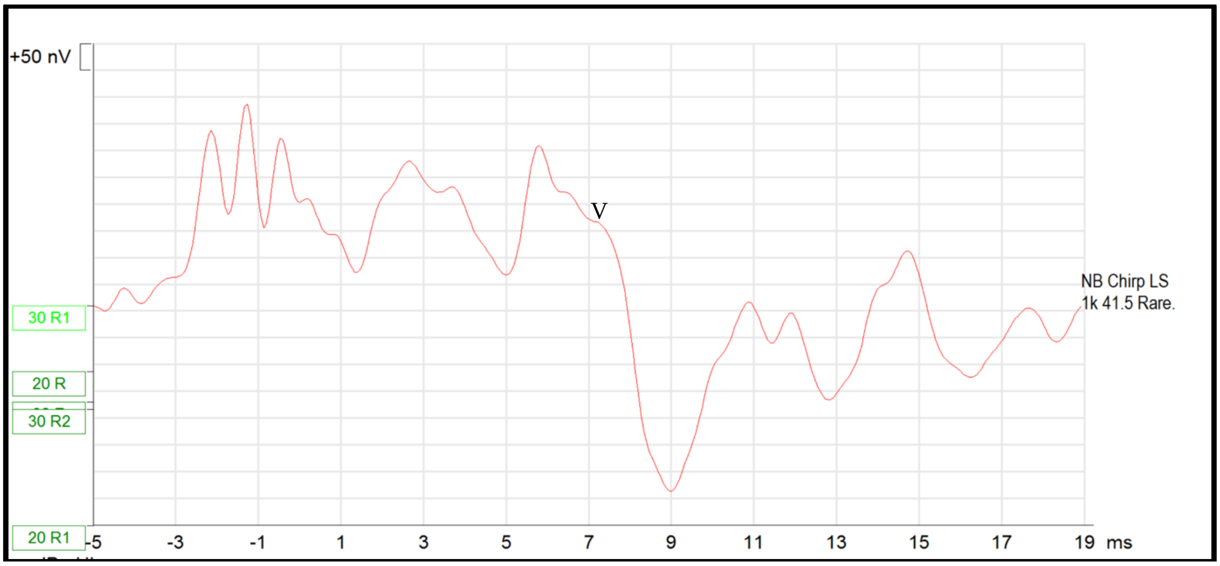

Figure 4.9. ABR-recording with the bobbin coil attached to the B250 transducer. The artefact is distinguishable in the interval (-3) to 1 ms. Wave V is observed at approximately 7,2 ms. Settings chosen are NB CE-chirp with 1000 Hz, 30 dB nHL (Table 4.10, Index 16).

5. DISCUSSION

The overall results obtained in synthetic VEMP and ABR measurements, indicate a reduction of the electromagnetic artefact using the bobbin coil. Although the reduction varies depending on test configuration, all measurements imply a reduction. The most significant decrease throughout the test series, was obtained in the synthetic ABR measurements where a reduction of 93.5% was reached using tone bursts at a frequency of 250 Hz (*Table 4.8*). In contrast to the values obtained in synthetic ABR, a minimum reduction of 9.5 % was obtained in synthetic cVEMP with bursts of 500 Hz at 75 dB nHL (*Table 4.4*). This variation in reduction may be caused by several different factors. For instance, the electrode cable layout was found to have significant impact on the artefact amplitude. To ensure a relatively constant area of the wire loop throughout the eight tests performed on each subject, the wires were taped to the table (Figure 3.4). However, a factor that was not considered beforehand, is the angle of the incoming magnetic field lines to the plane formed by the wire loop. If the field lines cross the loop at an angle of 90 degrees, the maximum amount of flux penetrates the loop. On the other hand, if the magnetic field lines are parallel to the plane (0 degrees), no flux enters the loop. As the magnetic flux, **B**, increases, so does the artefact, **ε** (*Equation 2.6*). Continuity throughout the synthetic measurements, is achieved to the highest extent possible. However, when attaching the bobbin coil during a test series, small changes in the layout of the electrode wires can cause relatively large deviations in the results. Partially due to the area of the loop, but also due to its angle to the magnetic field lines. The area of the wire loop as well as its angle to the magnetic field lines, are parameters that are inevitably changed when switching between subjects. Therefore, moving the electrodes further away from the transducer along a spherical surface, does not necessarily mean that the electromagnetic artefact decreases. This may explain why the artefact amplitude does not decrease in cVEMP when switching from S2 to S3 (*Table 4.5, Table 4.6*).

The bobbin coil seems to reduce the electromagnetic artefact more significantly on 250 Hz than 500 Hz. However, the intensity level does not seem to have any significant impact on the percentual reduction, except from in the cVEMP measurements. In cVEMP, test configurations with different intensities but same frequencies, seem to provide a larger variation in percentual reduction, unlike synthetic oVEMP and ABR. This may be due to the alternating balance in electrode impedances throughout the measurements. As mentioned before, when attaching the bobbin coil during a test series, some test parameters can change. In addition to the alterations of the wire loop's angle and area, caused by small changes of electrode wire layout, the electrode impedances are sensitive to alterations as well. If the electrodes are balanced differently in tests with and without the bobbin coil attached, the measured amplitude may be affected. The electrode impedances have a tendency to drop with time as the electrode contact improves, which might also affect the measured artefact amplitude. Furthermore, attachment of the bobbin coil may cause small changes in transducer placement, despite the markings intended for the B250. The variation in percentual reduction depending on intensity in synthetic cVEMP tests, might be due to changes in one or many of the factors mentioned above.

The synthetic ABR measurements seem to follow a certain pattern, judging from Figure 4.3. As the distance between electrodes and transducer increases, the artefact amplitude decreases. However, some of the measurements with the bobbin coil attached, indicates the opposite. Some of the synthetic ABR results including the coil, may be inaccurate since it was difficult to distinguish a waveform, probably due to very weak signals (*<110 nV*). These recordings have a relatively low resolution, which complicates the analysis.

Compared to synthetic VEMP, the ABR measurements included significantly lower stimuli intensities, which explains the relatively small artefact amplitudes. In VEMP measurements, no similar patterns are distinguished (Figure 4.1, Figure 4.2).

Whether a reduction corresponding to the theoretical estimation is achieved, cannot be confirmed. The electrode positions closest to the B250 are found in subject 1, for which the inverting electrode (*red*) is placed at a distance of approximately 5 centimeters from the B250 in all measurements. These recordings indicate a reduction of the artefact amplitude far greater than 25%, in most test configurations. A measured reduction in volt corresponds to an equal reduction of the magnetic flux according to equation 2.6, given that the area is constant. However, placing one bipolar electrode at a distance of 5 centimeters from the transducer, along a spherical and asymmetrical surface, does not mean that the artefact is measured at that distance. Artefacts are measured across the wire loop formed by the active electrode (*white*), inverting electrode (*red*) and the conductive material of the watermelon between the attachment points of these electrodes. Therefore, a reduction of 25% at a distance of 5 centimeters from the transducer, cannot be confirmed.

In ABR on a human subject, a percentual reduction of the artefact is observed in nearly all measurements except from the tests performed with the LS NB CE-Chirps® at 500 Hz. A clearly distinguishable artefact is present in recordings without the bobbin coil attached, however, no artefacts were noticeable in recordings including the bobbin coil (Figure 4.6, Figure 4.7). A possible explanation to this observation, might be the low intensity level in comparison to the tone burst stimuli of 40 dB nHL. This might also be due to a sufficiently efficient damping of the artefact. Based on visual estimation of waveforms in Figure 11 and 12, one might assume that the artefact is completely extinguished by the bobbin coil. It should be noted that these measurements, equal to the synthetic tests, are dependent of factors such as area of the wire loop, angle of the wire loop to the magnetic field lines, as well as balance in electrode impedances. These are all parameters that could have been slightly altered when the bobbin coil was attached. Despite these potential inaccuracies, it was possible to calculate a percentual reduction in most test configurations, resulting in a mean reduction of approximately 55 % using a 250 Hz tone burst and 52 % using the LS NB CE-Chirps® at 1000 Hz.

As stated in the theory section concerning ABR, latencies and amplitudes of waveform components are dependent of several factors. An ABR response can, with some certainty be distinguished in measurements with chirp stimuli at 500 Hz and 1000 Hz. The wave V latency in adults, using a LS NB CE-Chirps® at 500 Hz and 20 dB nHL, is approximately 7.97 milliseconds [22]. For chirp stimuli at 1000 Hz and 30 dB nHL, the wave V latency is 7.35 milliseconds in adults [22]. Using this information, one can approximately distinguish the wave V component according to the markings in Figures 4.6 - 4.9. Consequently, it is reasonable to assume that these recordings are in fact real ABR responses. However, measurements using a 250 Hz tone burst, resulted in less distinct recordings. The recorded waveforms do include components that are somewhat similar to those obtained in chirp recordings, but with longer latencies. Tone bursts are known to provide longer latencies than LS NB CE-Chirp© signals, due to the fact that these chirps are positioned earlier on the timeline [22]. Additionally, the waveform components are level dependent; meaning that an increased intensity level results in shorter latencies, vice versa [7]. Wave V latencies for tone bursts with low intensity and frequency might be as long as 16 milliseconds [22]. This information could possibly motivate that wave V components in Figures 4.4 - 4.5 can be distinguished at latencies of approximately 16 milliseconds.

It would be preferable to compare the results obtained in these measurements with an exact numerical latency for tone bursts of 250 Hz at specific intensity levels. Since no such values were found, a wave V component in Figures 4.4 - 4.5 cannot be marked out with certainty, and therefore left blank. Although it is not possible to verify that an ABR response is present in recordings using a 250 Hz tone burst, there are some similarities to an expected ABR waveform. Regardless of the accuracy in these ABR recordings, the results imply a reduction of the artefact using the bobbin coil.

According to nearly all results obtained in this study, a significant reduction of the electromagnetic artefact is achieved using a bobbin coil as a supplementary component to the B250. These results do imply that a bobbin coil can be used in order to reduce the problem of electromagnetic artefacts in VEMP and ABR measurements. We do believe that the obtained results are compelling and that they encourage further testing of the bobbin coil. Since this project is limited in both the number of test subjects and tests performed, due to the scope of the study, repeated tests on human subjects are needed to confirm the results obtained in this study. If further studies are carried out on this specific bobbin coil, one should consider a different way of attaching the coil to the mastoid, since the human subject experienced some discomfort due to the headband arrangement. A lot of tension was needed in order to keep the bobbin coil in place during the tests. This problem is also due to the mass of the bobbin coil, which is a factor one might want to consider in a potential remodeling of the coil. The current mass and size may cause issues if the bobbin coil principle is to be evaluated on infants and small children in the future, when the electrodes must be placed closer to the transducer.

In summary, if the benefit of using the bobbin coil can be verified, this method may be of interest in taking steps towards a clinical application of the B250.

6. CONCLUSIONS

The problem definitions, stated in section 1.4, are answered accordingly in the list below:

I. The bobbin coil does in fact cause a reduction of the electromagnetic artefact in all measurements where a comparison between measurements with and without the coil, was possible. The degree of reduction varies depending on test configuration; nevertheless, the Bobbin coil seems to have greater impact at 250 Hz than at 500 Hz. A wide variation in percentual reduction is noticed, which leads to the conclusion that some measurements might have been influenced by changes in internal factors, such as electrode cable layout.

II. It is not possible to confirm a 25% reduction at 5 centimeters from the B250 through these measurements. The artefacts are measured across the loop formed by the electrode wires and the artificial human head, which in not equal to actually measuring the induced voltage at distance of 5 cm from the B250. However, a majority of the measurements performed closest to the B250 resulted in reductions greater than the theoretical estimation.

III. The short ABR test series performed on a human subject, resulted in a measurable reduction of the electromagnetic artefacts using tone bursts at 250 Hz and chirps at 1000 Hz. In contrast, using chirp stimuli at 500 Hz did not result in a measurable reduction even though a decrease was present through visual assessment of the recorded graphs (Figure 4.6, Figure 4.7).

IV. We believe that these results, indicating a reduction in a majority of the tests, encourage further studies and development of a bobbin coil, to reduce the electromagnetic artefact caused by the B250. Repeated measurements are needed in order confirm the benefit of this specific bobbin coil.

If further tests are carried out, one should consider a different way of attaching the bobbin coil to the mastoid. Furthermore, in the event of remodeling the bobbin coil, changes should primarily be made to reduce its weight and size which would be beneficial in tests on human subjects.

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APPENDICES

APPENDIX 1

Synthetic oVEMP

Index	Force [Newton]	Impedance [Ohm]	Red Impedance [Ohm]	White Impedance [Ohm]	Black Impedance [Ohm]	Blue Impedance [Ohm]	Number of stimul	Coil On/Off	Sub	Ipsila/Con	Frequenc	Stimuli level [dB]
1	10	1000	N/A	N/A	N/A	N/A	200	Off	A	Ipsila	250	55
2	10	1000	N/A	N/A	N/A	N/A	200	Off	A	Ipsila	250	65
3	10	1000	N/A	N/A	N/A	N/A	200	Off	A	Ipsila	500	55
4	10	1000	N/A	N/A	N/A	N/A	200	Off	A	Ipsila	500	65
5	9.5	900	N/A	N/A	N/A	N/A	200	On	A	Ipsila	250	55
6	9.5	900	N/A	N/A	N/A	N/A	200	On	A	Ipsila	250	65
7	9.5	900	N/A	N/A	N/A	N/A	200	On	A	Ipsila	500	55
8	9.5	900	N/A	N/A	N/A	N/A	200	On	A	Ipsila	500	65
9	9.5	750	N/A	N/A	N/A	N/A	200	Off	B	Ipsila	250	55
10	9.5	750	N/A	N/A	N/A	N/A	200	off	B	Ipsila	250	65
11	9.5	750	N/A	N/A	N/A	N/A	200	Off	B	Ipsila	500	55
12	9.5	750	N/A	N/A	N/A	N/A	200	Off	B	Ipsila	500	65
13	9.5	750	N/A	N/A	N/A	N/A	200	On	B	Ipsila	250	55
14	9.5	750	N/A	N/A	N/A	N/A	200	On	B	Ipsila	250	65
15	9.5	750	N/A	N/A	N/A	N/A	200	On	B	Ipsila	500	55
16	9.5	750	N/A	N/A	N/A	N/A	200	On	B	Ipsila	500	65
17	10	1400	N/A	N/A	N/A	N/A	200	Off	C	Ipsila	250	55
18	10	1400	N/A	N/A	N/A	N/A	200	Off	C	Ipsila	250	65
19	10	1400	N/A	N/A	N/A	N/A	200	Off	C	Ipsila	500	55
20	10	1400	N/A	N/A	N/A	N/A	200	Off	C	Ipsila	500	65
21	9.5	1200	N/A	N/A	N/A	N/A	200	On	C	Ipsila	250	55
22	9.5	1200	N/A	N/A	N/A	N/A	200	On	C	Ipsila	250	65
23	9.5	1200	N/A	N/A	N/A	N/A	200	On	C	Ipsila	500	55
24	9.5	1200	N/A	N/A	N/A	N/A	200	On	C	Ipsila	500	65

	Peak one [microVolt]	Peak two [microVo	Peak-to-Pea	Amplitude [microVolt]	Comment
1	37.16	-37.5	74.66	37.33	
2	101.4	-92.5	193.9	96.95	
3	35.06	-31	66.06	33.03	
4	104.8	-93.6	198.4	99.2	
5	13.8	-12.3	26.1	13.05	
6	35.09	-31.6	66.69	33.345	
7	14.32	-12.8	27.12	13.56	
8	44.06	-42	86.06	43.03	5/8/2020 16:05
9	31.92	-31.6	63.52	31.76	
10	-75.2	84.06	159.26	79.63	
11	-27	29.74	56.74	28.37	
12	-82	88.5	170.5	85.25	
13	14.92	-12.6	27.52	13.76	
14	36.66	-32.3	68.96	34.48	
15	-14.8	16	30.8	15.4	
16	-45.2	57.05	102.25	51.125	5/8/2020 15:05
17	28.44	-32.6	61.04	30.52	
18	78.29	-81.2	159.49	79.745	
19	17.01	-15.3	32.31	16.155	Unikt mönster - triangelform
20	52.82	-47	99.82	49.91	
21	-4.87	5.099	9.969	4.9845	
22	-14	14.93	28.93	14.465	
23	12.54	-12.2	24.74	12.37	
24	40.79	-39.3	80.09	40.045	5/8/2020 16:56

APPENDIX 2

Synthetic cVEMP:

Index	Force [Newton]	Impedance [Ohm]	Red Impedance [Ohm]	White Impedance [Ohm]	Black Impedance [Ohm]	Blue Impedance [Ohm]	Number of stimul	Coli On/Off	Sub	Ipsila/Con	Frekvens	Stimuli level [dB]
1	10	1300	N/A	N/A	N/A	N/A	200	Off	A	Ipsila	250	55
2	10	1300	N/A	N/A	N/A	N/A	200	Off	A	Ipsila	250	65
3	10	1300	N/A	N/A	N/A	N/A	200	Off	A	Ipsila	500	55
4	10	1300	N/A	N/A	N/A	N/A	200	Off	A	Ipsila	500	65
5	9.5	1300	N/A	N/A	N/A	N/A	200	On	A	Ipsila	250	55
6	9.5	1300	N/A	N/A	N/A	N/A	200	On	A	Ipsila	250	65
7	9.5	1300	N/A	N/A	N/A	N/A	200	On	A	Ipsila	500	55
8	9.5	1300	N/A	N/A	N/A	N/A	200	On	A	Ipsila	500	65
9	10	1000	N/A	N/A	N/A	N/A	200	Off	B	Ipsila	250	55
10	10	1000	N/A	N/A	N/A	N/A	200	Off	B	Ipsila	250	65
11	10	1000	N/A	N/A	N/A	N/A	200	Off	B	Ipsila	500	55
12	10	1000	N/A	N/A	N/A	N/A	200	Off	B	Ipsila	500	65
13	10	1000	N/A	N/A	N/A	N/A	200	On	B	Ipsila	250	55
14	10	1000	N/A	N/A	N/A	N/A	200	On	B	Ipsila	250	65
15	10	1000	N/A	N/A	N/A	N/A	200	On	B	Ipsila	500	55
16	10	1000	N/A	N/A	N/A	N/A	200	On	B	Ipsila	500	65
17	10	1000	N/A	N/A	N/A	N/A	200	Off	C	Ipsila	250	55
18	10	1000	N/A	N/A	N/A	N/A	200	Off	C	Ipsila	250	65
19	10	1000	N/A	N/A	N/A	N/A	200	Off	C	Ipsila	500	55
20	10	1000	N/A	N/A	N/A	N/A	200	Off	C	Ipsila	500	65
21	9.5	1000	N/A	N/A	N/A	N/A	200	On	C	Ipsila	250	55
22	9.5	1000	N/A	N/A	N/A	N/A	200	On	C	Ipsila	250	65
23	9.5	1000	N/A	N/A	N/A	N/A	200	On	C	Ipsila	500	55
24	9.5	1000	N/A	N/A	N/A	N/A	200	On	C	Ipsila	500	65

	Peak one [microVolt]	Peak two [microVo	Peak-to-Pea	Amplitude [microVolt]	Comment
1	34.79	-37.7	72.49	36.245	
2	89.64	-81.3	170.94	85.47	
3	-23.2	24.15	47.35	23.675	
4	-71.4	71.76	143.16	71.58	
5	-22	19.06	41.06	20.53	
6	51.69	-58.2	109.89	54.945	
7	-18.8	20.23	39.03	19.515	
8	-67	62.54	129.54	64.77	2020511 12:22
9	24.15	-23.2	47.35	23.675	
10	59.91	-54.5	114.41	57.205	
11	25.92	-27.6	53.52	26.76	
12	75.6	-78.9	154.5	77.25	
13	-6.84	4.747	11.587	5.7935	Ingen vikt avläsning - avikande ljud -
14	-23.3	21.91	45.21	22.605	Ingen vikt avläsning
15	-14.2	14.21	28.41	14.205	Ingen vikt avläsning
16	47.52	-53.4	100.92	50.46	Ingen vikt avläsning- 20200511 1:29
17	-34.9	31.06	65.96	32.98	
18	-80.8	82.25	163.05	81.525	
19	26.39	-24.4	50.79	25.395	
20	79.46	-74.9	154.36	77.18	
21	-5.64	6.562	12.202	6.101	flera peaks med samma värde
22	-27.4	23.34	50.74	25.37	
23	11.54	-11.3	22.84	11.42	
24	39.93	-39.6	79.53	39.765	20200511 16:19

APPENDIX 3

Synthetic ABR:

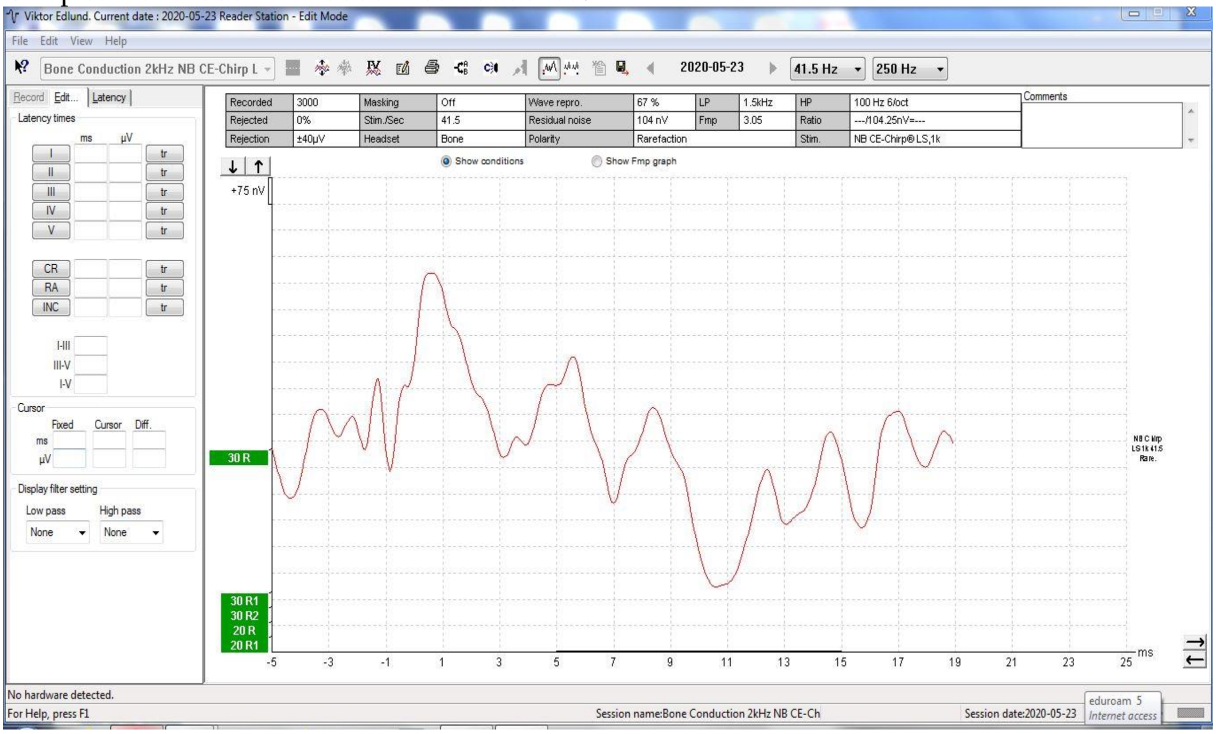
Index	Force [Newton]	Impedance [Ohm]	Red Impedance [Ohm]	White Impedance [Ohm]	Black Impedance [Ohm]	Blue Impedance [Ohm]	Number of stimul	Coli On/Off	Sub	Ipsila/Con	Frekvens	Stimuli level [dB]
1	9.5	1700	1700	< 500	600	1700	1000	Off	A	n/a	250	20
2	9.5	1700	1700	< 501	600	1700	1000	Off	A	n/a	250	30
3	9.5	1700	1700	< 502	600	1700	1000	Off	A	n/a	250	40
4	9.5	1700	1700	< 503	600	1700	1000	Off	A	n/a	500	20
5	9.5	1700	1700	< 504	600	1700	1000	Off	A	n/a	500	30
6	9.5	1700	1700	< 505	600	1700	1000	Off	A	n/a	500	40
7	9	1900	1900	500	600	1000	1000	On	A	n/a	250	20
8	9	1900	1900	500	600	1000	1000	On	A	n/a	250	30
9	9	1900	1900	500	600	1000	1000	On	A	n/a	250	40
10	9	1900	1900	500	600	1000	1000	On	A	n/a	500	20
11	9	1900	1900	500	600	1000	1000	On	A	n/a	500	30
12	9	1900	1900	500	600	1000	1000	On	A	n/a	500	40
13	9.5	1600	1600	750	750	600	1000	Off	B	n/a	250	20
14	9.5	1600	1600	750	750	600	1000	Off	B	n/a	250	30
15	9.5	1600	1600	750	750	600	1000	Off	B	n/a	250	40
16	9.5	1600	1600	750	750	600	1000	Off	B	n/a	500	20
17	9.5	1600	1600	750	750	600	1000	Off	B	n/a	500	30
18	9.5	1600	1600	750	750	600	1000	Off	B	n/a	500	40
19	9	1300	1300	600	600	800	1000	On	B	n/a	250	20
20	9	1300	1300	600	600	800	1000	On	B	n/a	250	30
21	9	1300	1300	600	600	800	1000	On	B	n/a	250	40
22	9	1300	1300	600	600	800	1000	On	B	n/a	500	20
23	9	1300	1300	600	600	800	1000	On	B	n/a	500	30
24	9	1300	1300	600	600	800	1000	On	B	n/a	500	40
25	9.5	1200	1000	1200	600	500	1000	Off	C	n/a	250	20
26	9.5	1200	1000	1200	600	500	1000	Off	C	n/a	250	30
27	9.5	1200	1000	1200	600	500	1000	Off	C	n/a	250	40
28	9.5	1200	1000	1200	600	500	1000	Off	C	n/a	500	20
29	9.5	1200	1000	1200	600	500	1000	Off	C	n/a	500	30
30	9.5	1200	1000	1200	600	500	1000	Off	C	n/a	500	40
31	9	1100	1100	1000	600	500	1000	On	C	n/a	250	20
32	9	1100	1100	1000	600	500	1000	On	C	n/a	250	30
33	9	1100	1100	1000	600	500	1000	On	C	n/a	250	40
34	9	1100	1100	1000	600	500	1000	On	C	n/a	500	20
35	9	1100	1100	1000	600	500	1000	On	C	n/a	500	30
36	9	1100	1100	1000	600	500	1000	On	C	n/a	500	40

	Peak one [microVolt]	Peak two [microVo	Peak-to-Pea	Amplitude [microVolt]	Comment
1	-0.24	0.282	0.522	0.261	
2	-0.86	0.829	1.689	0.8445	
3	-2.64	2.695	5.335	2.6675	
4	0.136	-0.11	0.246	0.123	
5	0.37	-0.4	0.77	0.385	
6	1.267	-1.29	2.557	1.2785	
7	0.039	-0.06	0.099	0.0495	Difficult to find Amplitude value but
8	-0.12	0.146	0.266	0.133	
9	0.526	-0.48	1.006	0.503	
10	0.049	-0.01	0.059	0.0295	Difficult to find Amplitude value but
11	0.097	-0.06	0.157	0.0785	
12	-0.26	0.273	0.533	0.2665	20200511 19:43
13	-0.16	0.27	0.43	0.215	
14	-0.55	0.702	1.252	0.626	
15	-2.47	1.916	4.386	2.193	
16	-0.11	0.117	0.227	0.1135	
17	-0.35	0.351	0.701	0.3505	
18	-1.27	1.218	2.488	1.244	
19	-0.058	-0.03	0.028	0.014	barely noticeable
20	-0.12	0.127	0.247	0.1235	
21	-0.42	0.458	0.878	0.439	
22	-0.04	0.049	0.089	0.0445	
23	-0.15	0.185	0.335	0.1675	
24	-0.51	0.458	0.968	0.484	21:11 och 20:43
25	-0.14	0.166	0.306	0.153	
26	-0.43	0.536	0.966	0.483	
27	-1.54	1.69	3.23	1.615	
28	-0.09	0.107	0.197	0.0985	
29	0.273	-0.29	0.563	0.2815	
30	-0.86	0.88	1.74	0.87	
31	-0.01	0.058	0.068	0.034	Hard to distinguish - poor sample
32	-0.11	0.097	0.207	0.1035	Hard to distinguish - ev poor sample
33	-0.37	0.39	0.76	0.38	
34	0.058	-0.03	0.088	0.044	Hard to distinguish
35	-0.09	0.136	0.226	0.113	
36	-0.39	0.351	0.741	0.3705	22:14

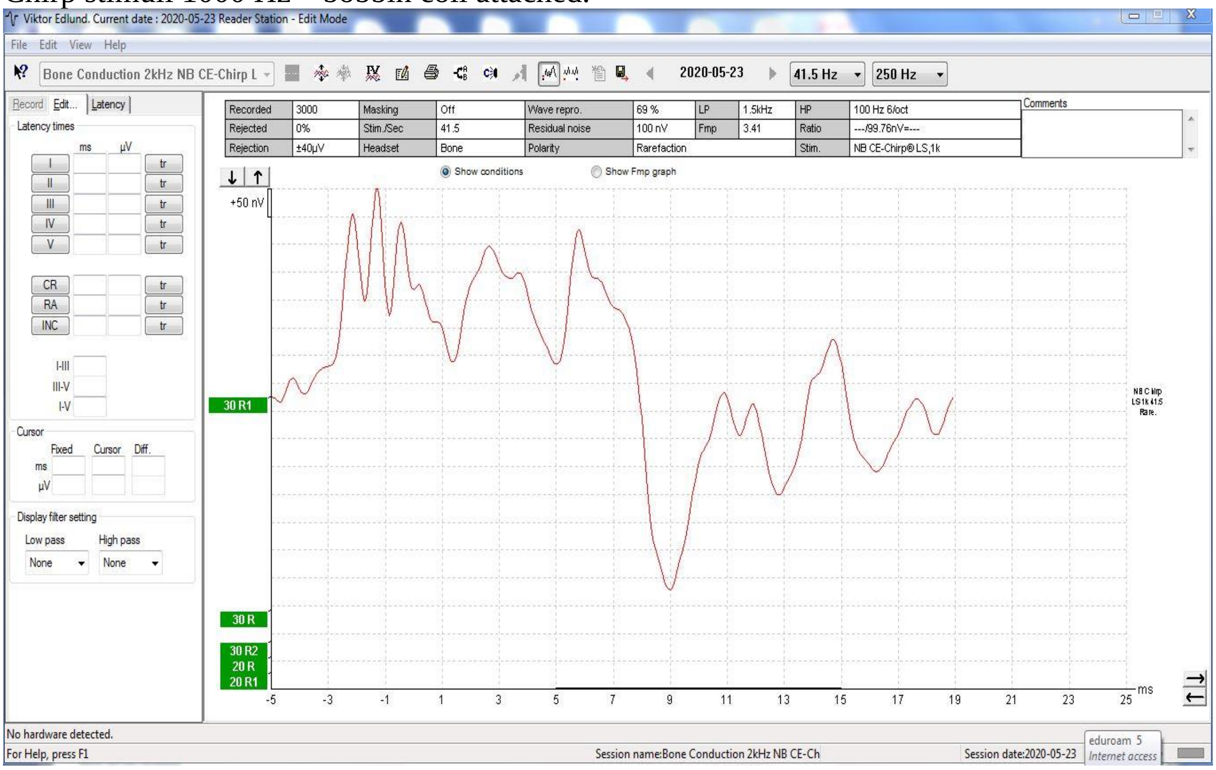
APPENDIX 4

Human ABR:

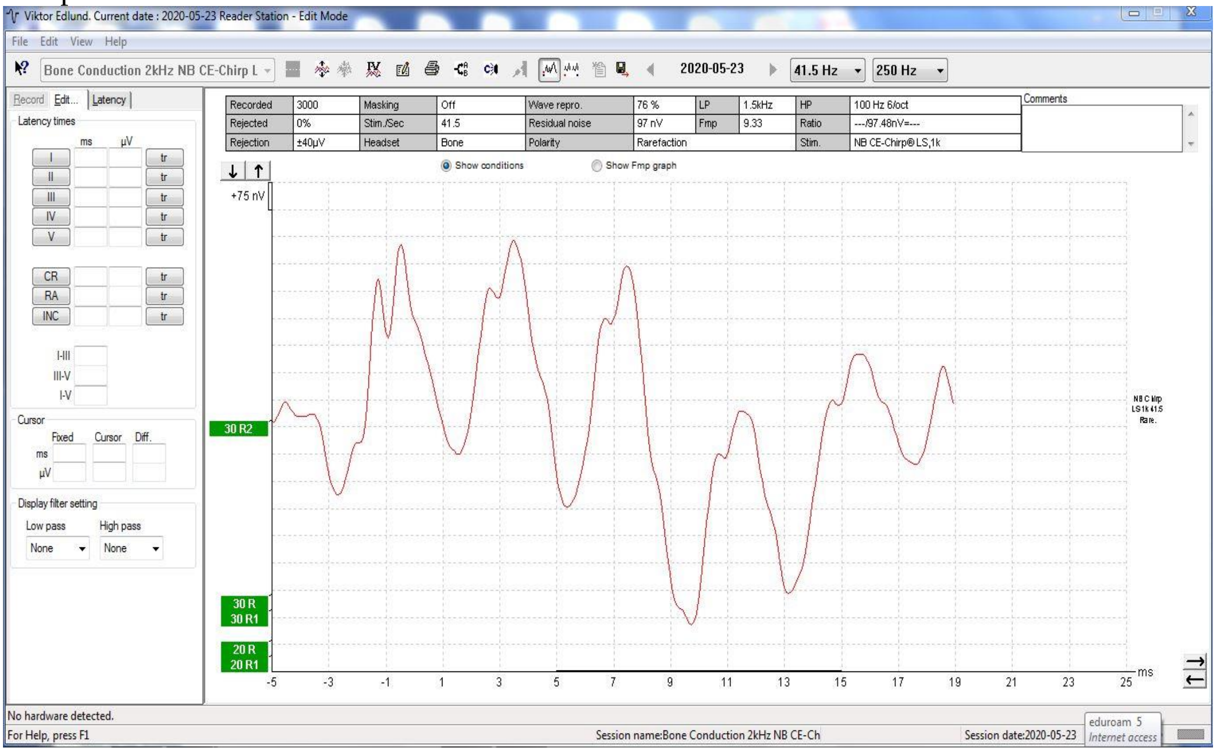
Chirp stimuli 1000 Hz – bobbin coil attached.



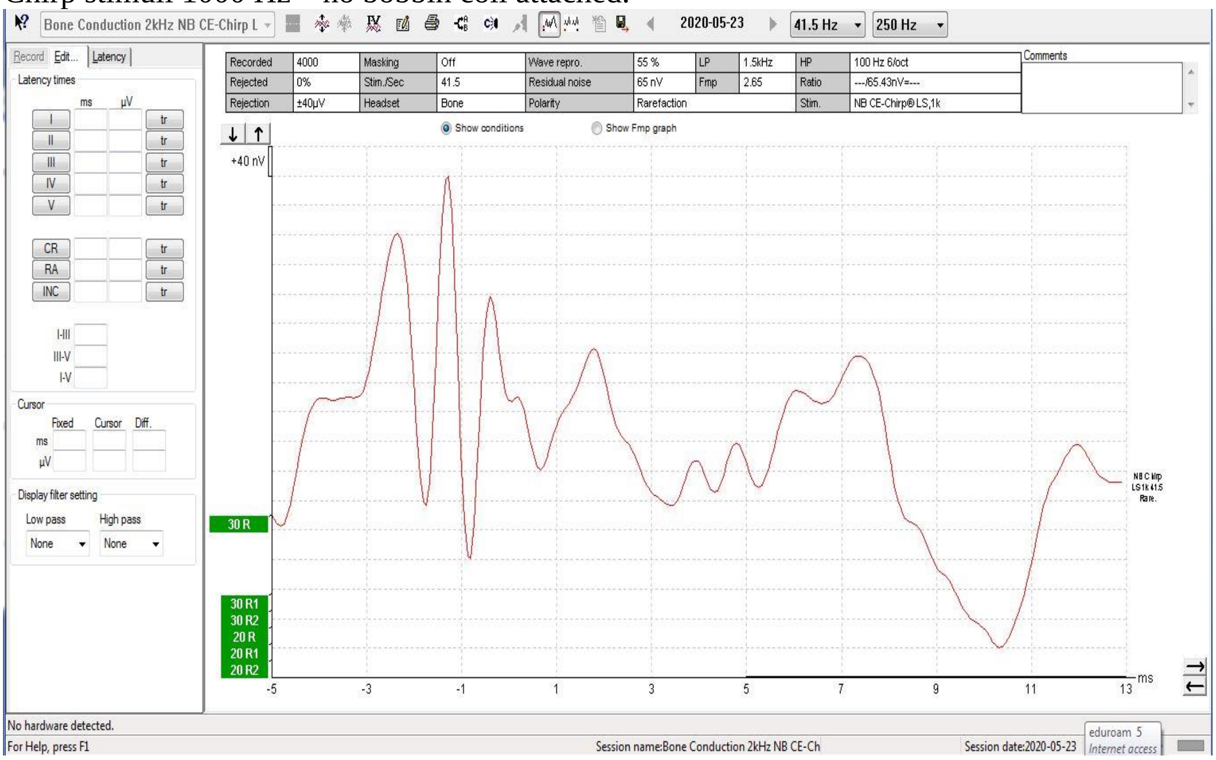
Chirp stimuli 1000 Hz – bobbin coil attached.



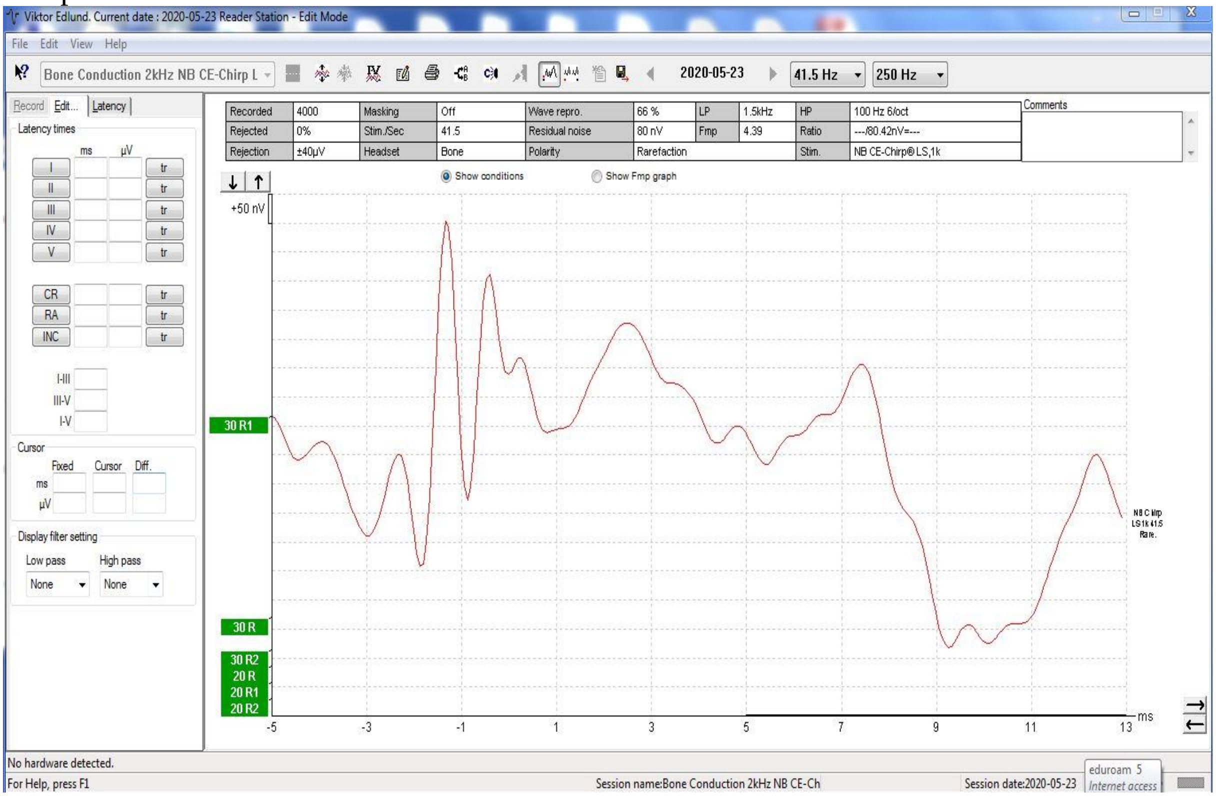
Chirp stimuli 1000 Hz – bobbin coil attached.



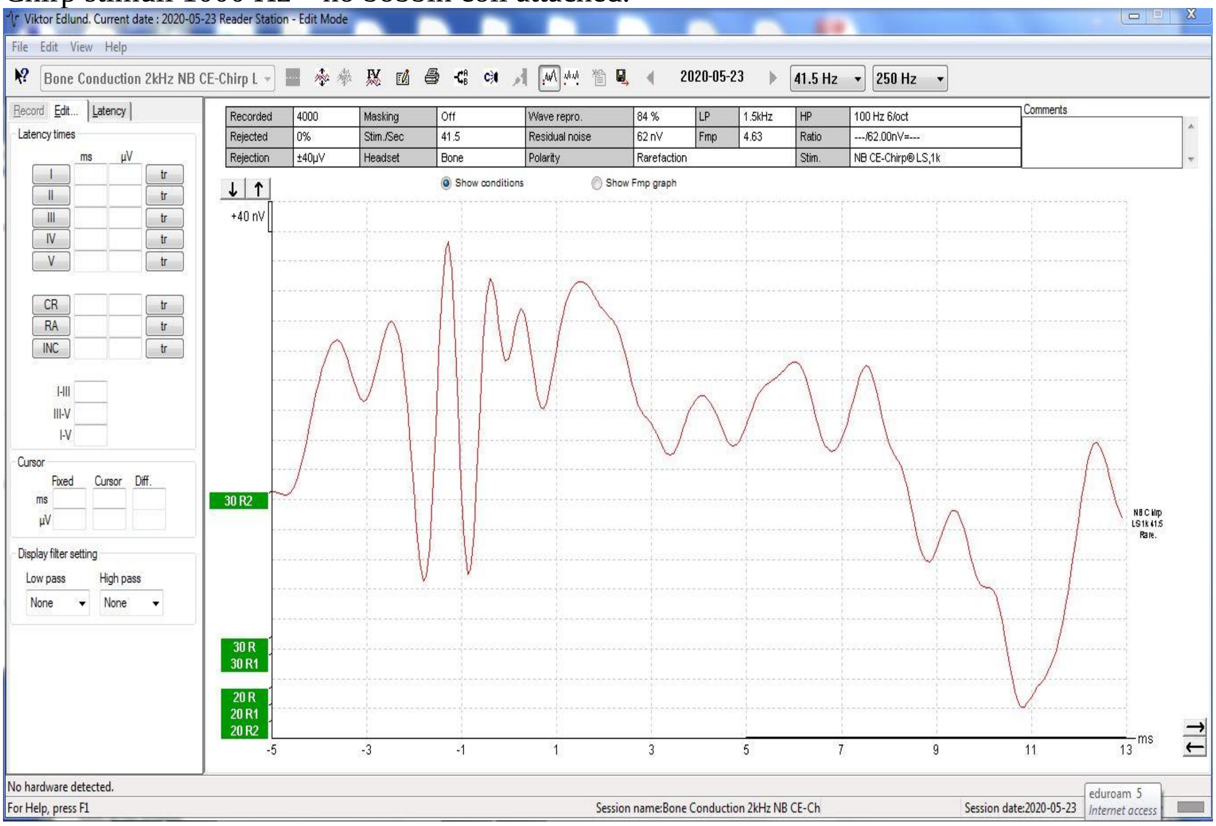
Chirp stimuli 1000 Hz – no bobbin coil attached.



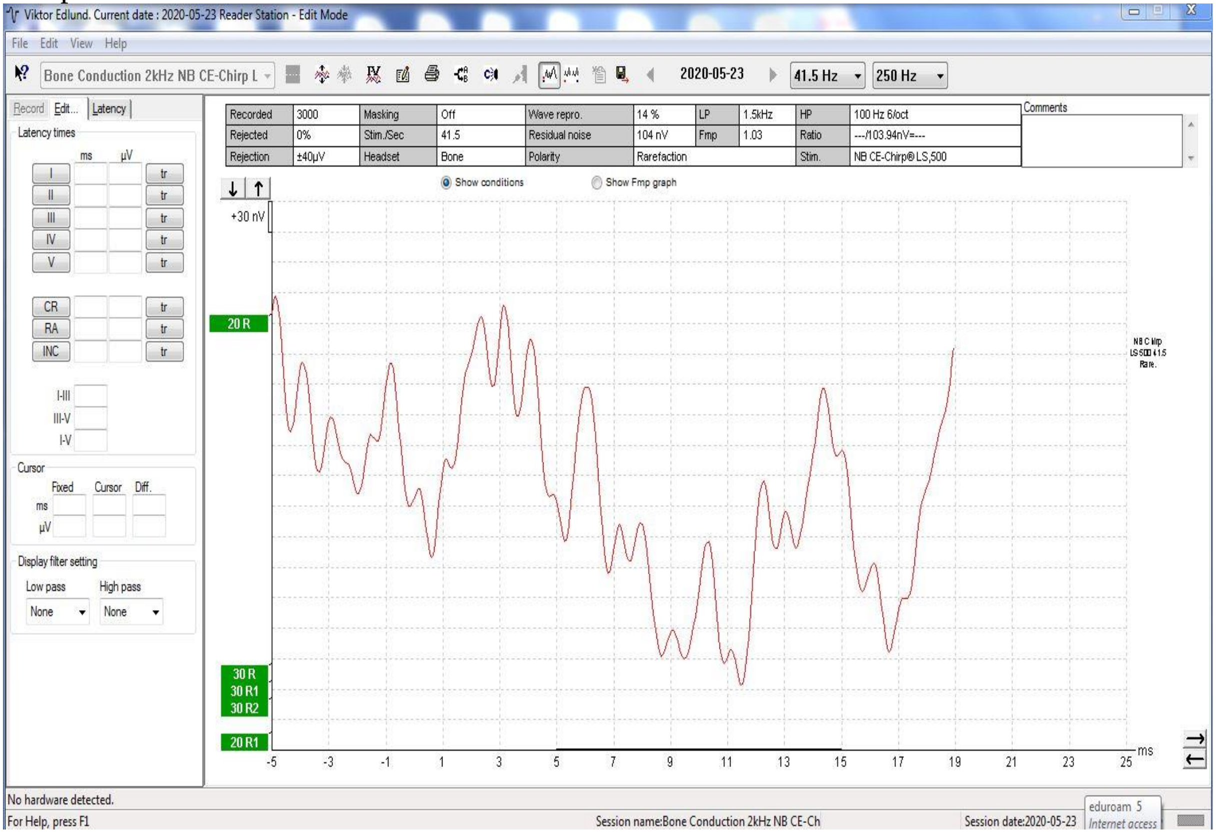
Chirp stimuli 1000 Hz – no bobbin coil attached.



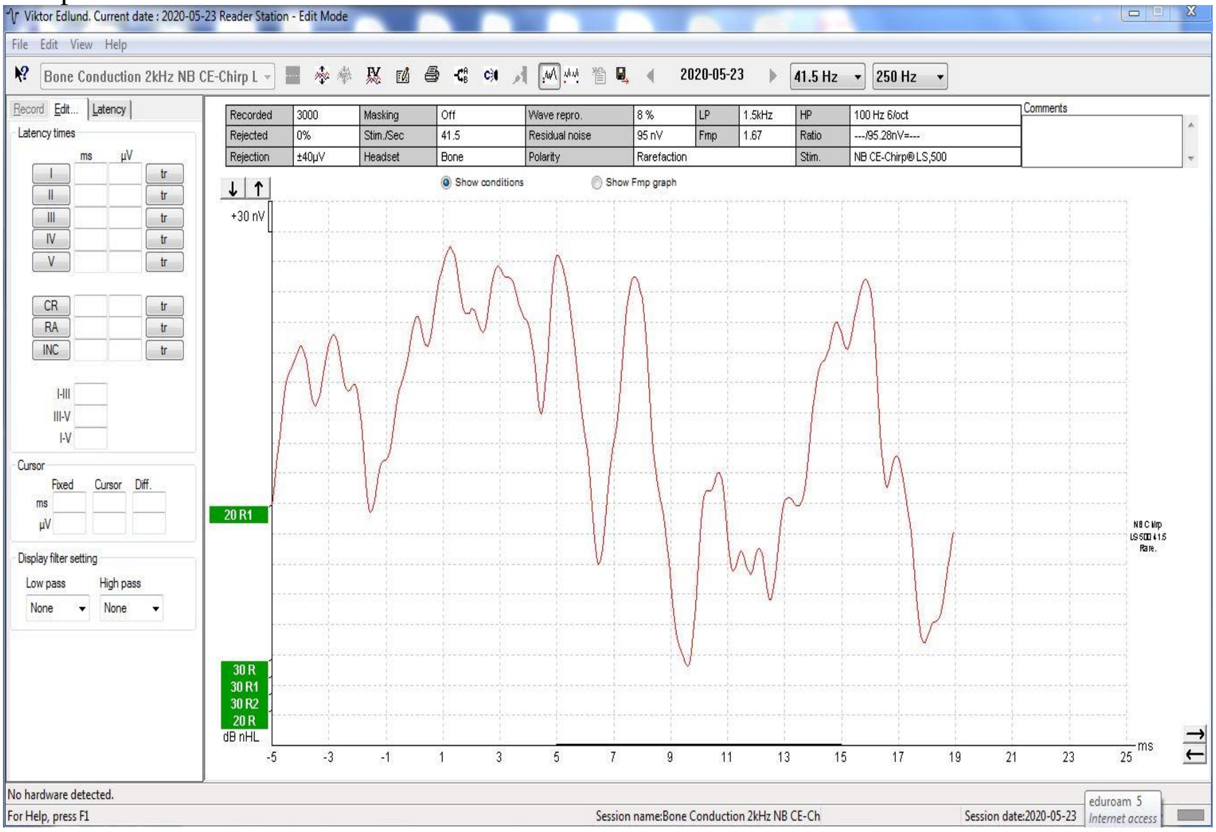
Chirp stimuli 1000 Hz – no bobbin coil attached.



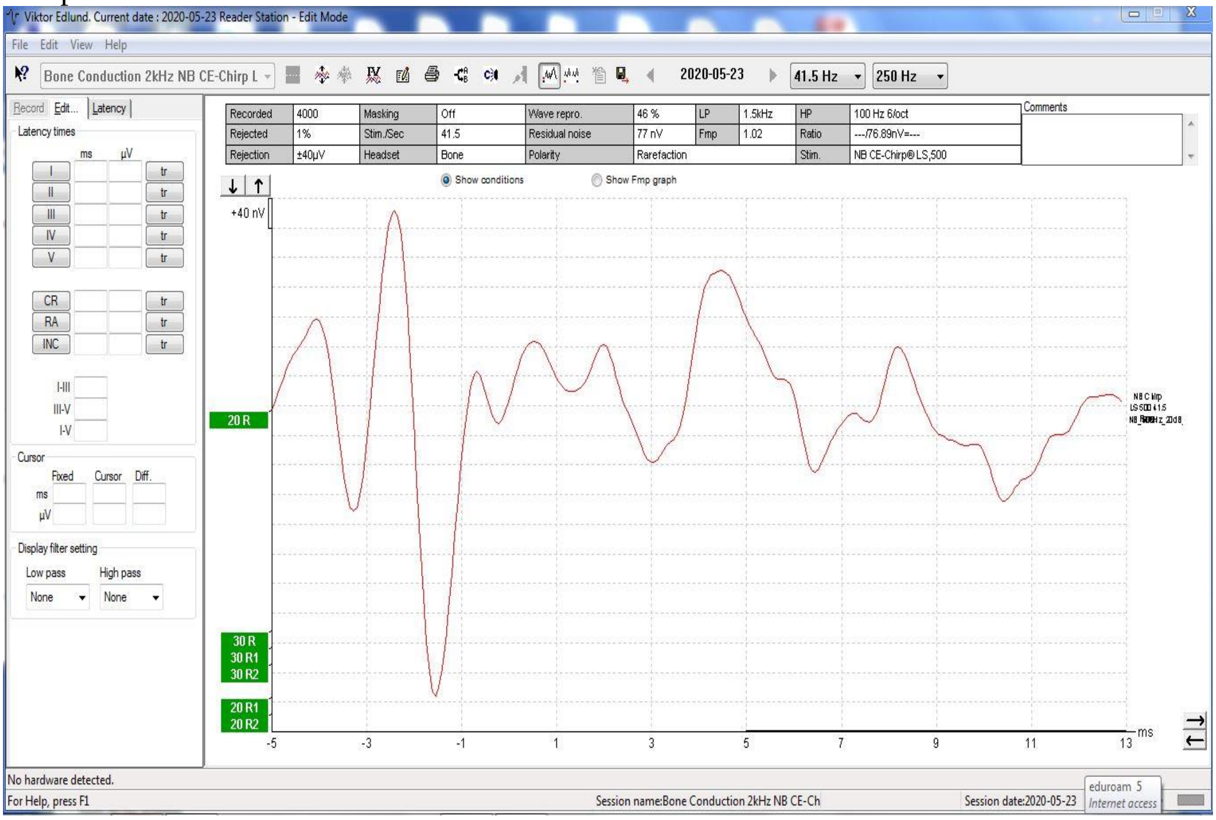
Chirp stimuli 500 Hz – bobbin coil attached.



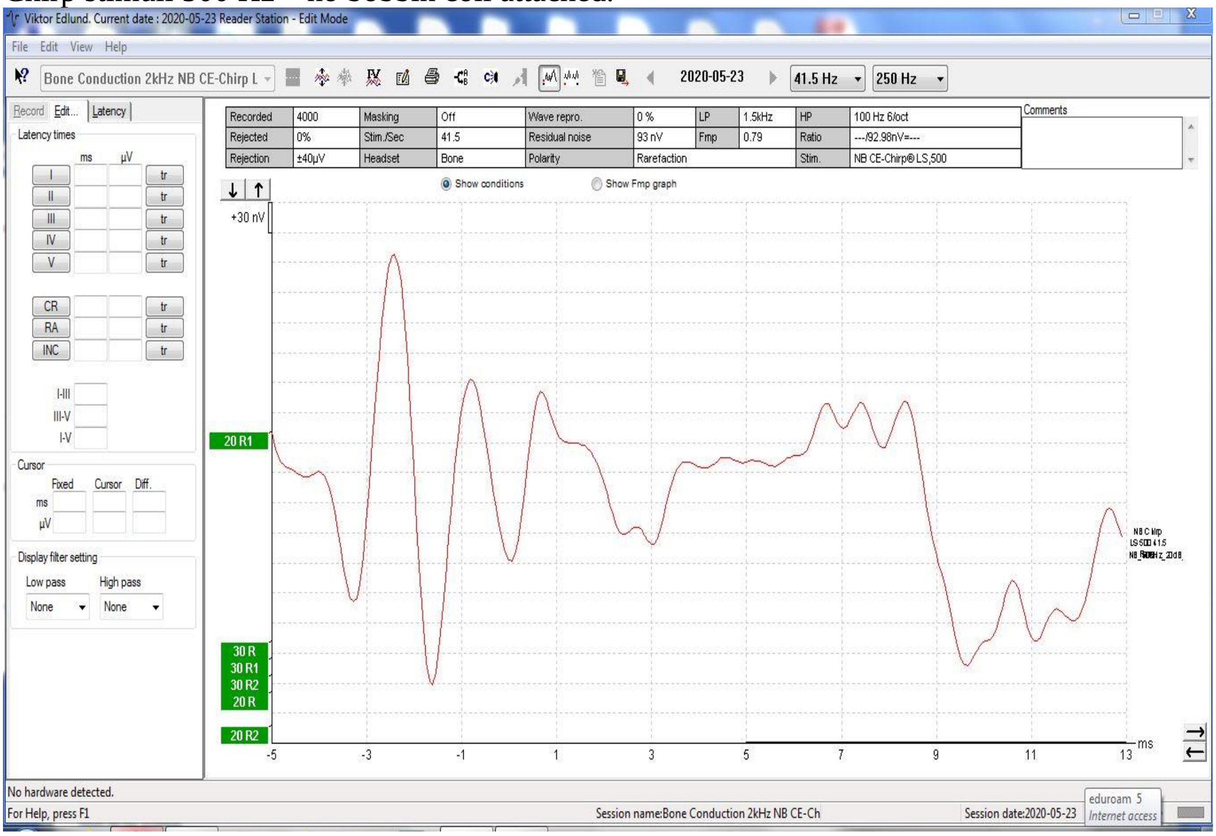
Chirp stimuli 500 Hz – bobbin coil attached.



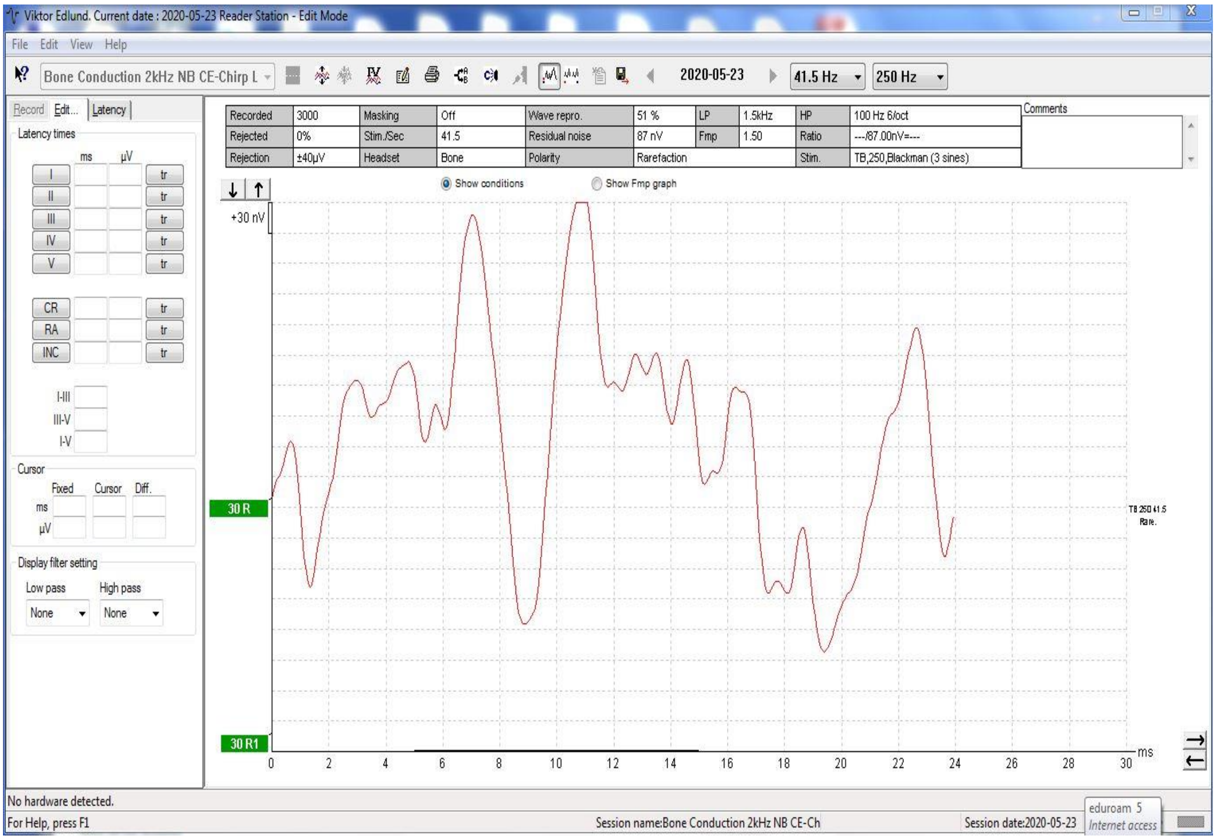
Chirp stimuli 500 Hz – no bobbin coil attached.



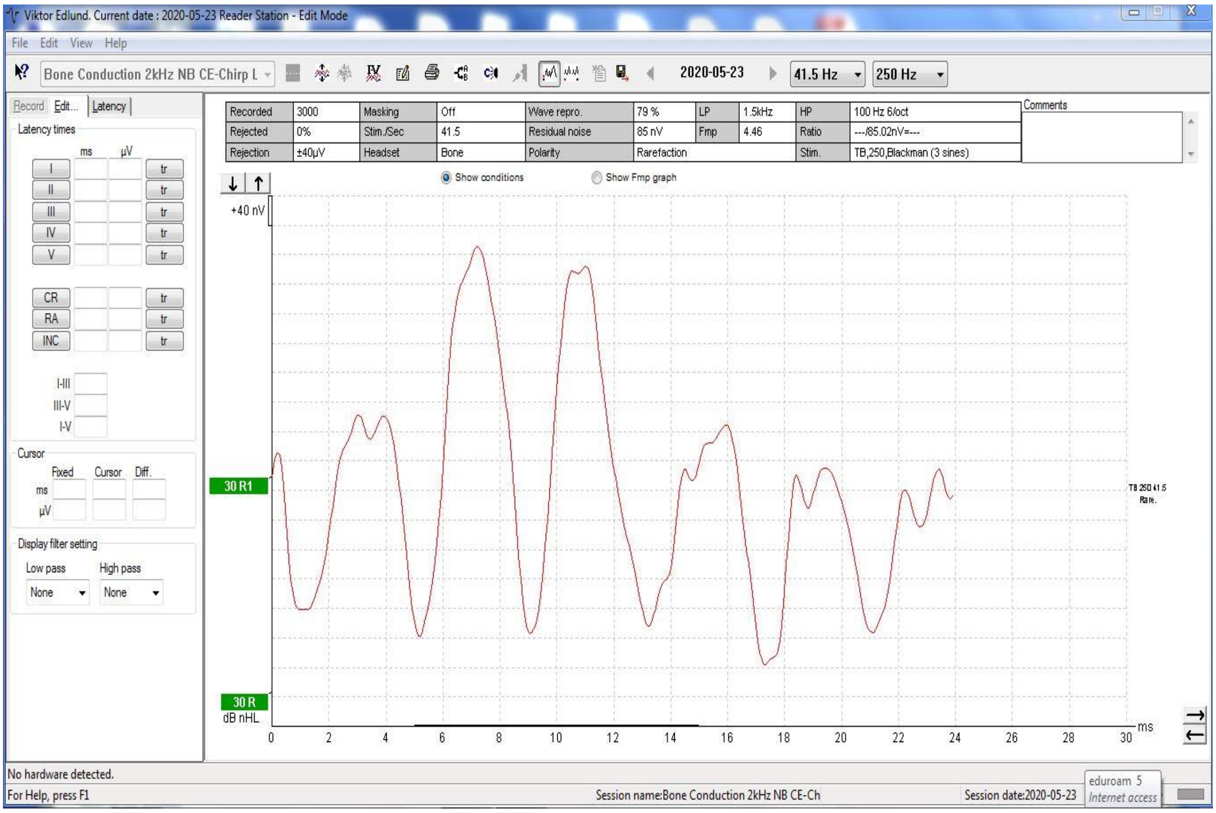
Chirp stimuli 500 Hz – no bobbin coil attached.



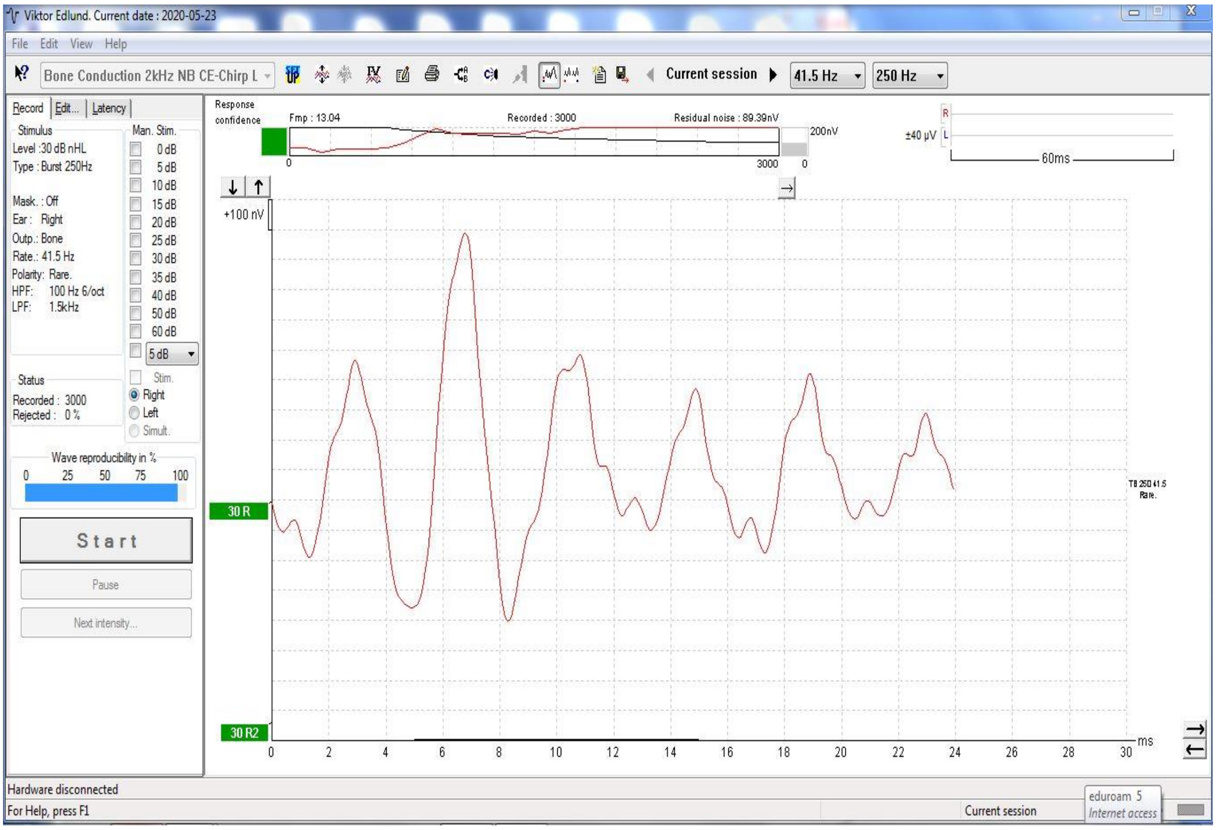
Tone burst stimuli 250 Hz – bobbin coil attached.



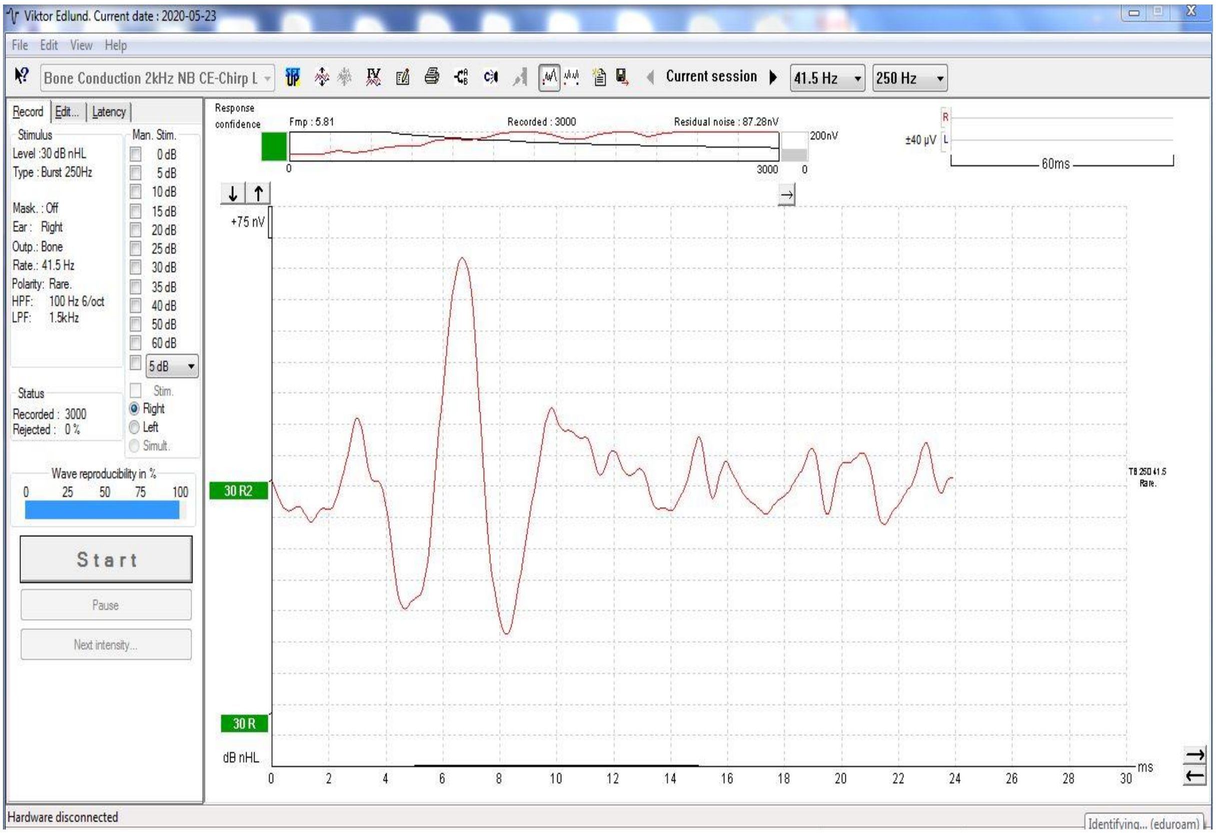
Tone burst stimuli 250 Hz – bobbin coil attached.



Tone burst stimuli 250 Hz – no bobbin coil attached.



Tone burst stimuli 250 Hz – no bobbin coil attached.



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