Brainstem Evoked Response Audiometry via Bone Conduction
The Clinical Assessment of Conductive Hearing Losses

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Abstract

Background
To prevent a delay in the speech and/or language development of a child, early diagnosis of a hearing loss is crucial. Since it can be difficult to administer pure tone audiometry (PTA) in young children, brainstem evoked response audiometry (BERA) is often used. In this field, a new type of stimulus was designed: the LS CE-Chirp. This stimulus not only compensates for the cochlear travelling wave delay, but also for the upward spread of excitation at higher levels, and an increased change of the cochlear neural delay with frequency at lower levels.

Purpose
The first aim of this study was to discern patients with a cognitive hearing loss from normal hearing people and patients with retrocochlear pathology in otoneurological measurements. The second aim was to examine how BERA and PTA thresholds correlate, using the LS CE-Chirp.

Methods
ABRs evoked by the LS CE-Chirp of 24 participants were analysed in this study. PTA was performed in octaves between 250 and 8000 Hz via AC without and with plug, and between 500 and 4000 Hz via BC without plug. BERA BB and NB measurements, at 1000 and 4000 Hz, were performed via AC and BC, without and with plug. BC BERA measurements were performed with the inverting electrode in retro- and pre-auricular position. The auditory brainstem thresholds and wave latencies were visually interpreted and defined by two independent clinicians.

Results
The results showed that for AC measurements, wave latencies were significantly longer in the condition with plug than in the condition without plug; but for BC measurements, there was no significant difference in wave latencies between the two conditions. The results did not show significant different interwave intervals between the two conditions. Besides, the wave latencies were significantly shorter in AC measurements than in BC measurements. The results also showed that there was no significant effect of electrode position on the latencies of the waves nor the interwave intervals.

Furthermore, the results showed that, overall, the correlation coefficients represented moderate to strong effects. But, a correction factor is needed to predict PTA thresholds by BERA thresholds, at 1000 and 4000 Hz in both AC and BC measurements. The correction factors for the combined data in this study, at 1000 Hz (p = .797b) and 4000 Hz (p =.801b) in AC measurements are recommended for the use in clinical practice.

Conclusion
The findings showed that BC measurements can discern patients with a conductive hearing loss from normal hearing people and patients with retrocochlear pathology. In addition, the findings showed that BERA thresholds can accurately predict PTA thresholds when a correction factor is used.

Keywords
Conductive hearing loss, Brainstem evoked response audiometry, Pure tone audiometry, Air conduction, Bone conduction, LS CE-Chirp.
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1. Introduction

To acquire language, good and sufficient input from the environment is needed. However, that is not the only condition for a normal language development. A child has to have intact hearing. If not, the input of the environment can be less or not heard and understood. This leads to a delay in the language development of the child, in both comprehensive and productive manner (Schaerlaekens, 2008). It is thus of supreme importance that difficulties in hearing are recognized as early as possible. Once the type of hearing loss is assessed the treatment can be started. For example, children with a conductive hearing loss caused by otitis media with effusion can get tubes, and children with a sensorineural hearing loss qualify for a hearing aid or cochlear implant.

The type of hearing loss can be diagnosed by analysing the results of a hearing test. By administering pure tone audiometry, the hearing ability can be assessed. For this measurement, the patient has to give a behavioural response when a sound is heard. In this way, the patient’s thresholds for different frequencies can be obtained. A threshold is the smallest stimulus intensity eliciting a response (Hyvärinen, 2012). However, administering pure tone audiometry can be very difficult, especially in young children (younger than three years old) or children with a low concentration level (Kemaloğlu, Gündüz, Gökmen, & Yilmaz, 2005).

An alternative measurement to objectively assess the hearing ability of children is brainstem evoked response audiometry, obtained by using air conduction and bone conduction stimuli.

In this study, the additional value of brainstem evoked response audiometry via bone conduction in the clinical assessment of a conductive hearing loss will be explored. Furthermore, it will be examined whether objective thresholds obtained via brainstem evoked response audiometry correlate with subjective thresholds obtained via pure tone audiometry to assess the degree of hearing loss.

1.1 The auditory system

The ear is divided into of three parts: the outer ear, the middle ear and the inner ear (see Figure 1).

The outer ear consists of the auricle, the ear canal and the tympanic membrane. The auricle functions as a locator and catches the sound in the air. The sound travels via the ear canal to the tympanic membrane causing it to vibrate. There it reaches the middle ear.

The middle ear consists of the tympanic cavity and the ossicles: the malleus, the incus and the stapes. By the vibrations of the tympanic membrane the ossicles are put in motion. The function of the middle ear is to transfer the sound coming from the outer ear (through air) to the inner ear (to fluid: perilymph). However, there is a difference in impedance between air and perilymph. The impedance of air is lower than that of perilymph causing a loss of sound (Lamoré, 2008). The ossicles are compensating for this loss by functioning as an amplifier.

The inner ear is situated in the mastoid and consists of the vestibular system (the semicircular canals) and the cochlea. The cochlea consists of three canals: the scala vestibuli, the scala tympani and the scala media (see Figure 2). The scala vestibuli and the scala media are separated from each other by Reissner’s membrane, and the scala media and the scala tympani are separated from each other by the basilar membrane. At the basilar membrane, in the scala media, lies the organ of Corti. This organ holds the inner and outer hair cells, which can be stimulated by movement of the basilar membrane, caused by the movement of perilymph due to the vibrating stapes in the oval window. The basilar membrane is relatively narrow and stiff at the base, but wide and flexible at the apex. This contributes to its tonotopical organization: high frequencies are processed at the base and low frequencies at the apex. The inner and outer hair cells stimulate the spiral ganglion cells and neural information subsequently travels through the auditory nerve to the brainstem (Fuller, Pimentel, & Perego, 2012; Hyvärinen, 2012).

![Figure 2. Cross-section through the cochlea and close-up of the organ of Corti. Retrieved from https://kids.frontiersin.org/article/10.3389/frym.2015.00008 (adapted).](image)

1.1.1 Measuring the sensitivity of the ear
The ear sensitivity for sounds can be measured by administering audiometry. Thresholds are obtained for each ear via air conduction (AC) and bone conduction (BC) and plotted in an audiogram. When sound is presented via AC (through headphones or insert earphones) the sound waves travel through the outer, middle and inner ear to the brain. In contrast, the bone conductor is placed on the mastoid, bringing the cochlea into vibration, whereby the outer and middle ear processes are skipped.

1.1.2 Hearing losses
A variety of damages to the ear can cause a hearing loss. A distinction is made between the thresholds obtained via AC and the thresholds obtained via BC, since they might differ from each other. This difference is called the air-bone gap (Fuller et al., 2012). There are three types

In a conductive hearing loss, the thresholds obtained via AC show a hearing loss, while the thresholds obtain via BC do not show a hearing loss (so there is an air-bone gap).

In a sensorineural hearing loss, the thresholds obtained via AC are equal to the thresholds obtained via BC, but they both show a hearing loss (so there is no air-bone gap).

In a mixed hearing loss, both AC and BC thresholds show a hearing loss, indicating both conductive and sensorineural hearing loss components.

1.2 Audiometry
There are two forms of audiometry: subjective audiometry and objective audiometry.

1.2.1 Subjective Audiometry
The most commonly applied type is pure tone audiometry (PTA). Here, the patient has to give a behavioural response when a sound is heard. Because the assessment of the hearing ability is depending on the response of the patient, PTA is a subjective test. The subjects requirement to comprehend and concentrate to the task of responding is essential. This can be very difficult to achieve in young children (Kemalouglu et al., 2005; Statten & Wishart, 1956).

1.2.2 Objective audiometry
Objective audiometry is based on obtaining auditory evoked potentials via electroencephalography (EEG), so no active (subjective) response of the patient is required.

Auditory Evoked Potentials
Auditory evoked potentials (AEPs) are changes of the electrical activity of the brain shown on the EEG, produced by auditory stimuli. AEPs consist of positive and negative fluctuations of the brain activity (waves) that follow the stimulus in a time-locked manner (Plourde, 2006). AEPs are divided into three parts (see Figure 3). The first part up to approximately 10 ms after the stimulus, is called the auditory brainstem response (ABR). The second part immediately follows the ABR and continues for approximately 40 ms; it is called the middle latency response (MLR). The third part begins 50-100 ms after the stimulus and is called the long latency response (LRR; Hyvärinen, 2012; Melcher, 2009).

Figure 3. Stylized auditory evoked potential in humans (Hyvärinen, 2012), adapted from (Melcher, 2009).
AEPs are characterized by amplitude and latency. The amplitude is defined as the distance (in 
µV) between the peak of the wave and the following trough. The amplitude of the response 
depends on the intensity and rate of presentation of the stimulus. An increase in intensity causes 
an increase of the amplitude, while an increase of stimulus rate causes a decrease of the 
amplitude. The latency is the time between stimulus onset and the occurrence of the wave in 
question. The latency of the waves is determined by the source of the neural activity (Hyvärinen, 
2012; Lamoré, 2008; Melcher, 2009; Plourde, 2006).

AEPs are classified as either transient or steady-state. When the stimulus rate is slow 
enough for the response to wear off before the next stimulus, the given response is called a 
transient AEP. Transient responses are characterized by their latency and amplitude. Brainstem 
evoked response audiometry uses this type of AEP and is analysed in the time domain. When 
the stimulus is delivered fast enough to cause overlap of the individual responses of the 
individual transient responses, the given response is called steady-state AEP. Steady-state 
responses are characterized by their phase and amplitude and are analysed in the frequency 
domain. The auditory steady-state response uses this last type of AEP in the assessment of one’s 
hearing (Plourde, 2006).

Brainstem Evoked Response Audiometry
The transient response in brainstem evoked response audiometry (BERA) in the first 10 ms 
after stimulus presentation normally contains six waves, each corresponding to the neural 
activity of a specific structure in the neural pathway to the brain. The waves are numbered with 
Roman numerals (I-VI; see Figure 3). Wave I originates from the beginning of the auditory 
nerve, wave II from the end of the auditory nerve, wave III from the cochlear nucleus, wave IV 
from the olivary complex, wave V from the lateral lemniscus and wave VI from the colliculus 
inferior (Hyvärinen, 2012; Lamoré, 2008).

Clinically, the most important waves are wave I, III and V. Wave V is the most 
prominent; it is even visible at intensity levels near threshold. Because of this, wave V is most 
commonly used in clinical practice to objectively determine auditory thresholds (Hyvärinen, 
2012; Lamoré, 2008).

1.3 Chirp Research
BERA measurements are built upon the latency and amplitude of waves. The clarity of the ABR 
depends on the synchronization of the neural activity: the better the synchronization, the clearer 
the waves are visible. To obtain optimal neural synchronization, a stimulus should be used that 
can compensate for the cochlear travelling wave delay (Dau, Wegner, Mellert, & Kollmeier, 
2000). Since high frequencies are located at the base and low frequencies at the apex of the 
cochlea, low frequencies arrive later than high frequencies when a click stimulus is used, 
because this type of stimulus presents all frequencies at the same time. To compensate for that 
cochlear travelling wave delay, the chirp was developed (CE-Chirp; Elberling & Don, 2008). 
The chirp can be described as a short sound where the frequency of a sine wave glides quickly 
upwards, based on a model that compensates for intracochlear travelling wave times (see Figure 
4; Hyvärinen, 2012): the low frequencies come first followed by higher frequencies. In this way, 
the frequencies in the cochlea are stimulated simultaneously. This makes the chirp an actual 
broadband stimulus, because its ABR represents the activity of both high and low frequencies, 
which ensures optimal neural synchronization (Dau et al., 2000; Elberling, Don, Cebulla, & 
Stürzebecher, 2007; Fobel & Dau, 2004).
Besides the broadband chirp, which stimulates the frequencies from 200 up to 10 000 Hz in the cochlea, four octave-band chirps of 500, 1000, 2000 and 4000 Hz are developed, that are based on decomposing the broadband chirp into several narrowband stimuli (see Figure 5; Elberling & Don, 2010).

The chirp compensates for the cochlear travelling wave delay, but the studies of Fobel and Dau (2004) and Elberling and Don (2008) suggest that there is an influence of the level of stimulation on the efficiency of the chirp. Elberling, Callø and Don (2010) investigated this by testing five different chirps. They found that the shorter chirps were the most efficient at higher levels of stimulation, while the longer chirps were the most efficient at lower levels. It is suggested that two different mechanisms are responsible for this: (1) upward spread of excitation at higher levels, and (2) an increased change of the cochlear-neural delay with frequency at lower levels. To control for the influence of these two mechanisms, Elberling and Don (2010) designed the ‘level specific’ chirp: LS CE-Chirp.

So the LS CE-Chirp compensates not only for the cochlear travelling wave delay, but also for these two mechanisms. Because of this, the amplitude of wave V is greater (Cargnelutti, Cóser, & Biaggio, 2017; Cho et al., 2015; Kristensen & Elberling, 2012), which makes BERA measurements more efficiently with the LS CE-Chirp than with other stimuli that are still used.
BERA responses are used for two different purposes: auditory threshold measurements and otoneurological measurements.

In otoneurological measurements, latencies and interwave intervals are examined to detect possible tumours and other lesions in the auditory pathway, which are called retrocochlear pathologies. A prolongation in neural conduction time between the structures generating waves I and V can be caused by a lesion (Hyvärinen, 2012; Lamoré, 2008). The place of this prolongation (in the ABR) indicates where in the brainstem the lesion finds its place. Thus, an increased I-V interwave interval is an indication of a retrocochlear pathology.

BERA can also be used to detect a conductive hearing loss. The ABR of a patient with a conductive hearing loss shows prolonged latencies and reduced amplitudes of all waves. As the conductive component increases, the waves prior to wave V become less well defined and may even be absent. Consequently, the I-V interwave interval may not be determined (Fowler & Durrant, 1994). As a conductive hearing loss prolongs the latencies of all waves, the interwave intervals are not increased.

In BERA, a sensorineural hearing loss cannot be detected. Cho et al. (2015) measured a normal hearing group and a group of patients with sensorineural hearing loss. The normal hearing group showed a wave V latency of 4.46 ms (0.46) at 80 dB nHL and 5.54 ms (0.43) at 60 dB nHL. The group of patients with sensorineural hearing loss showed a wave V latency of 4.32 ms (0.37) at 80 dB nHL and 5.67 ms (0.31) at 60 dB nHL. There seems to be no difference in the latency of wave V at 80 dB and 60 dB nHL between normal hearing people and patients with sensorineural hearing loss. Also, there was no difference in amplitude of wave V between the normal hearing group and the group of patients with sensorineural hearing loss.

Although the advantages of the LS CE-Chirp are clear, the click stimulus is still used (Abhilash, Shankar, & Somanna, 2017; Bakhos et al., 2017; Birkent et al., 2017; Singh, Agrawal, Choudhary, & Ranjan, 2018), since the click is still considered a golden standard in ABR measurements.

Ceylan, Gümüşgün and Feratlar (2018) compared ABR wave V latencies, wave V amplitudes and procedural times using the click and the CE-Chirp in patients with bilateral sensorineural hearing loss. They used the Eclipse EP15 ABR system and the stimuli were delivered at a rate of 20.1/s with alternating polarity. Results showed that there was no significant difference between wave V latencies of the click and the CE-Chirp. The researchers also found that, at high intensities (90 and 100 dB), wave V amplitudes of the click were higher than wave V amplitudes evoked by the CE-Chirp. Finally, they found that the procedural time for the CE-Chirp was shorter than for the click.

A comparison between the LS CE-Chirp and the click has also been made. Cargnelutti et al. (2017) compared the absolute latencies of wave I, III and V, the interwave intervals I-III, III-V and I-V, the amplitude values of wave V and its association with the amplitude of wave I, and the interaural difference of wave V in the ABR. They used the Eclipse EP25 ABR system with the click and the LS CE-Chirp at 85 dB nHL, with a stimulus rate of 17.1/s and alternating polarity. The researchers stimulated 30 normal hearing participants via inserts. The results showed that there was no significant difference in the absolute latencies of wave I, III and V between the click and the LS CE-Chirp. However, there is controversy about whether there is a difference in the absolute latencies of wave I, III and V between the click and the LS CE-Chirp, considering that Kristensen and Elberling (2012) did find a significant difference between the absolute latencies of wave I, III and V between the click and the LS CE-Chirp. Cargnelutti et al. (2017) mention that the commercial version of the LS CE-Chirp, when using the Eclipse EP25 ABR system equipment manufactured by InterAcoustics) has been changed. In this version of the LS CE-Chirp, the location of the chirp corresponding to the 2500 Hz frequency is used as point zero instead of the location of the final frequency of 10,000 Hz of
the LS CE-Chirp used in research. This means that the difference in outcomes between the study of Kristensen and Elberling (2012) and Cargnelutti et al. (2017) can be explained by the different types of LS CE-Chirp that are used. Furthermore, the results showed that the amplitude of wave V was significantly greater for the LS CE-Chirp than the click. Finally, there was no significant interaural difference in wave V latencies. The authors conclude that the LS CE-Chirp is as efficient as the click to capture ABR at high levels of stimulation and that the LS CE-Chirp may be useful in neuroaudiological diagnosis because of its capability to evoke wave I, III and V, with the advantage of producing greater amplitude V waves than when evoked by the click. This is in contradiction with the results of Ceylan et al. (2018), who found that wave V amplitudes evoked by the click were higher than those evoked by CE-Chirp at high intensities. However, this corresponds with the differences between the CE-Chirp and the LS CE-Chirp (Kristensen & Elberling, 2012).

While a lot of research has been done to investigate the advantages of the chirp over the click in air conducted measurements. Cobb and Stuart (2016a) were the first to report a comparison of ABRs to bone conducted CE-Chirp and click stimuli. Their aim was to compare air and bone conducted wave V amplitudes and latencies evoked by the CE-Chirp with those evoked by the click and the tone burst in neonates. Cobb and Stuart (2016a) obtained the ABRs of 168 neonates evoked by AC and BC CE-Chirp (broadband and narrowband), click and tone burst stimuli. The frequency specific stimuli were presented at 500, 1000, 2000 and 4000 Hz. They used the GSI Audera (V2.7 software) ABR system with inserts and the B71 (with elastic headband) to present the stimuli. The results showed that wave V amplitudes to AC and BC CE-Chirps were significantly larger than those evoked by clicks and tone bursts. Further, wave V latencies to AC and BC CE-Chirps were significantly shorter than wave V latencies evoked by clicks and tone bursts, which is in contradiction to the results of Ceylan et al. (2018) who found no significant difference between wave V latencies evoked by the click and the CE-Chirp. This may be due to the use of different ABR systems. Cobb and Stuart (2016a) found no significant differences in the latencies of wave V between AC and BC measurements at 30 and 45 dB. They conclude that AC and BC CE-Chirps generate larger wave V amplitudes and shorter wave V latencies accounting for both the broadband and narrowband CE-Chirp, which makes it more efficient than click and tone burst stimuli.

Cobb and Stuart not only examined the ABRs of neonates, but also compared wave V amplitudes and latencies of neonates with those of adults (Cobb & Stuart, 2016b). They reused the ABRs of the neonates and obtained the ABRs of 20 adults with the same ABR system as in their first study, presenting the CE-Chirp with inserts or the B71. The results showed that wave V amplitudes were larger for adults than for neonates. For all AC conditions, wave V latencies were shorter for adults than for neonates. For BC conditions this depended on the intensity: at low intensities (15 and 30 dB) latencies were similar for neonates and adults, while at high intensities (45 dB), wave V latencies were shorter for neonates than for adults. The authors report that this finding is likely due to enhanced transmission of the auditory signal to the temporal bone in newborns; and that latency differences between neonates and adults are consistent with differences in click and tone burst stimuli: they reflect maturational differences as a function of age (Cobb & Stuart, 2016b; Seo et al., 2018).

Seo et al. (2018) evaluated the characteristics and the efficacy of BC ABR for the treatment of patients with hearing disorders. A limitation of AC ABR is that it can predict a hearing loss, but (on its own) it cannot determine the conductive component. BC ABR can estimate cochlear function and help identify any type of hearing loss that could be present. The authors report that the disadvantage of obtaining BC ABRs is that, in most cases, there is a large artefact which can obscure the first 1-2 ms. However, recently a new BC transducer was introduced: the RadioEar B81.
Keceli and Stenfelt (2018) compared wave V latency, amplitude and electrical artefacts between ABRs obtained via the B71 and B81. They used the Eclipse EP25 ABR system with tone bursts of 500, 2000 and 4000 Hz, clicks and broadband LS CE-Chirps at 20 and 50 dB nHL. The results showed that there was no significant difference in wave V latency and amplitude between the B71 and B81, but the B81 produces significantly smaller electrical artefacts than the B71.

Since BC ABRs are necessary to discern a cognitive hearing loss from other pathologies, it is essential that the contribution the LS CE-Chirp evoked by the B81 to this process is investigated.

Research has not only developed in the field of otoneurological measurements, but also in auditory threshold measurements. In this field, pure tone audiometry is the golden standard and a lot of researchers explore the correlation between PTA thresholds and thresholds of stimuli used in BERA.

El-Attar, Enass, Abu and Sanaa (2017) compared the correlation between AC and BC thresholds obtained via PTA, and ABR thresholds evoked by the click and the CE-Chirp (broadband and narrowband). They used the Eclipse EP25 ABR system with stimuli delivered by headphones or the B71. The results showed that the detectability of wave V near threshold was better using the CE-Chirp than the click. El-Attar et al. (2017) report that this is due to the capability to increased temporal synchrony of the CE-Chirp in comparison with the click (Cebulla, Lurz, & Shehata-Dieler, 2014; Maloff & Hood, 2014; Mühler, Rahne, & Verhey, 2013). Furthermore, the results showed that narrowband CE-Chirps had the highest correlation with PTA (500 Hz R = .87; 1000 Hz R = .58; 4000 Hz R = .75). These results are in contradiction with the results of Kestens, Van Yper, Beynon and Dhooge (2017) who compared thresholds obtained by narrowband CE-Chirps with PTA thresholds. They found no correlation between PTA thresholds and 500 Hz chirp thresholds, but good correlations between PTA thresholds and chirp thresholds at 1000, 2000 and 4000 Hz.

Ceylan et al. (2018) not only compared ABR wave V latencies, wave V amplitudes and procedural times, but they also compared ABR threshold values using the click and the CE-Chirp in patients with bilateral sensorineural hearing loss. They compared the correlation with PTA between the click and broadband CE-Chirp at 1000, 2000 and 4000 Hz. The results showed that CE-Chirp thresholds were closer to PTA thresholds at 1000 and 2000 Hz, but click thresholds were closer to PTA thresholds at 4000 Hz.

Overall, thresholds obtained via narrowband CE-Chirps show a good correlation with thresholds obtained via PTA. However, has not yet been investigated whether this is also true for the relatively new LS CE-Chirp. Since it is unknown when the LS CE-Chirp was implemented by the InterAcoustics ABR system, the results of earlier studies are questionable as regards to the stimulus that was used. Therefore, the current research is the only one so far comparing thresholds between PTA and BERA using the LS CE-Chirp.

1.4 Present study
The first aim of this study is to discern a conductive hearing loss from other pathologies and normal hearing people in otoneurological measurements. In normal hearing people, the latency of wave I and V fall within norms. However, in patients with a conductive hearing loss and in patients with retrocochlear pathology the latency of wave V is prolonged. The difference between these pathologies is that, in the case of a cochlear hearing loss, wave I is prolonged as well, while in the case of retrocochlear pathology wave I falls within norms (see Figure 6). In contrast to a conductive hearing loss, the I-V interwave interval of patients with retrocochlear pathology is increased. The problem in practice is that in both patients with a conductive hearing
loss and patients with retrocochlear pathology wave I is not always visible in the ABR due to bad signal-to-noise ratio in the EEG (see Figure 7; Fowler & Durrant, 1994; Mackersie & Stapells, 1994; McGee & Clemis, 1982; Seo et al., 2018).

Figure 6. The difference in latencies of wave I and V between normal hearing, a conductive hearing loss and retrocochlear pathology in measurements via AC.

Figure 7. The problem emerging in absence of wave I: there is no difference in the latency of wave V between patients with a conductive hearing loss and patients with retrocochlear pathology.

To solve this problem, it is suggested that BERA measurements obtained via BC can discern a conductive hearing loss from retrocochlear pathologies (Fowler & Durrant, 1994), because in BC measurements, the latency of wave V of both normal hearing people and patients with a conductive hearing loss fall within norms, while wave V latency of patients with retrocochlear pathology is prolonged (see Figure 8).

Figure 8. Measurements via BC can discern a conductive hearing loss from retrocochlear pathologies, because of the differences in wave V latencies: the latency of wave V in patients with a conductive hearing loss falls within norms, while the latency of wave V in patients with retrocochlear pathology is prolonged.

*It should be noted that the exact latencies of the waves in AC measurements could differ from those in BC measurements.

The second aim of this study is to examine how LS CE-Chirp BERA thresholds and PTA thresholds correlate. Earlier research has shown that there is a large correlation between objective measurements and PTA (Baldwin & Watkin, 2013; Gorga et al., 2006; Maloff & Hood, 2014; Stapells, Gravel, & Martin, 1995; Vander Werff, Prieve, & Georgantas, 2009). However, this is a conclusion based on the results of studies with a combination of other stimuli (click, tone burst, M-chirp (Dau et al., 2000)) and transducers (headphones, inserts). So there is a need to test how BERA and PTA thresholds correlate for the combination of the LS CE-Chirp with inserts and the B81 bone conductor.
This study aims to provide an answer to the following research questions:

1. In what way can brainstem evoked response audiometry via bone conduction be used to assess conductive hearing losses?
2. How can thresholds obtained via brainstem evoked response audiometry with air and bone conducted LS CE-Chirp stimuli predict thresholds obtained via pure tone audiometry?

The first hypothesis is that in patients with a conductive hearing loss, the latency of wave V is prolonged in AC measurements, while the latency of wave V in BC measurements are within norms; and that interwave intervals are not affected by a conductive hearing loss. To put this into perspective, normative latency data will be obtained for both AC and BC measurements.

The second hypothesis is that BERA thresholds evoked by the LS CE-Chirp can accurately predict PTA thresholds, since earlier research has shown this is true for other stimuli and transducers (as stated above). According to Ferguson (2009) correlation coefficients represent a small effect when $R = .20$, a moderate effect when $R = .50$ and a strong effect when $R = .80$. This study will investigate how BERA thresholds and PTA thresholds correlate and whether there is a need for a correction factor to predict PTA thresholds by BERA thresholds.
2. Methods and Materials

2.1 Participants
The participants were 24 adults of which 5 were male and 19 were female. Their age ranged between 18 and 76 years (median = 23) and they had no neurological problems (for more details, see appendix I).

2.2 Procedure
The measurements were performed at the ENT clinic of the Radboudumc in Nijmegen. Before the participants came to the hospital for the study, they were asked to answer the following questions: their name, date of birth, whether they had a history of brain damage or any problems with hearing and whether they were left or right handed (see Appendix I). They also got written information about the study and the informed consent.

At the time of the measurements, the participants were informed again and asked if they had any questions. All participants signed an informed consent on a voluntary basis.

The measurements began with performing the PTA via AC for both ears in octaves between 250 to 8000 Hz. After that, the PTA via BC was performed for the ear that would be tested with the BERA later, in octaves between 500 to 4000 Hz. The audiometrical test procedure was performed in conformity with the guidelines from the American Speech-Language-Hearing Association (2005).

After obtaining the PTA, the recording surface electrodes were applied. For this study, four electrodes were used and applied according to the International 10-20 system (Jasper, 1958): a ground electrode was placed at the left side of the forehead (Fp1), a non-inverting electrode was placed on the vertex (Cz) and two inverting electrodes were placed on the mastoid posterior (M1 or M2) and anterior (left or right red circle) of the tested ear (see Figure 10). In this study, the electrode positions on the mastoid will be referred to as retro-auricular (posterior mastoid) and pre-auricular (anterior mastoid). After the electrodes were applied, the participants were instructed to lie down on a bed with their eyes closed and asked to relax and, if possible, to sleep.

![Figure 10. The location of the electrodes used in this study: Cz (non-inverting electrode), Fp1 (ground electrode), M1 or M2 (first inverting electrode) and the left or right red circle (second inverting electrode), according to the International 10-20 system (Jasper, 1958), adapted from (Jafari & Mohsenin, 2010).](image)

After applying the electrodes, the impedance was checked to be below 5 kΩ. Thereafter, BERA measurements were performed conform the following procedure. First, one broadband and two narrowband measurements (AC or BC) were performed. The broadband measurement was an otoneurological measurement. It consisted of 2000 responses with condensation and 2000 responses with rarefaction polarity at 70 dB and 40 dB for AC measurements, and 40 dB only
for BC measurements. A summation of the polarities was used to define the wave I, III and V, since there is no significant difference between the latencies of waves evoked by stimuli with rarefaction or condensation polarity (Klaassen, 2016). The narrowband measurements were threshold measurements at 1000 and 4000 Hz. They consisted of 1000 responses with condensation and 1000 responses with rarefaction polarity at 70 dB (AC) or 40 dB (BC). The polarity with the clearest wave V was chosen to determine the auditory threshold. The threshold was set on the lowest intensity at which wave V was just visible. After these three measurements with one transducer, they were performed again with the other transducer. Frequencies and transducer type were randomized between participants. The broadband measurements via AC and the narrowband measurements (AC and BC) were only performed with the inverting electrode placed in retro-auricular position, while broadband measurements via BC were performed with the inverting electrode placed in both retro- and pre-auricular position. Furthermore, the tested ear was randomized between participants.

Subsequently, a plug was inserted in the tested ear. PTA measurements via AC were performed only on the tested ear with plug. One broadband and two narrowband BERA measurements via AC were performed as described above. Finally, a retro-auricular broadband measurement via BC was performed. The total test time was approximately 2.5 hours.

Auditory brainstem thresholds and wave latencies were visually interpreted and defined by two independent clinicians.

Appendix II shows an example of the procedure followed in BERA measurements.

### 2.3 Materials

For the PTA measurements, an InterAcoustics AD629 (audiometer) was used, with a TDH-39 supra-aural headphones (AC) and a RadioEar B-81 bone conductor (BC).

For the BERA measurements, an InterAcoustics Eclipse EP25 System® was used, with E-A-RTONE™ 3M insert earphones (AC) and a RadioEar B-81 (BC).

For the electrode placement, the skin was cleaned with disinfectant and scrubbed with Nuprep Skin Prep Gel. The electrodes (Kendall, Neonatal electrodes, 4203, prewired) were applied with Ten20 conductive paste. Ears were plugged using E-A-R™ 3M Classic™ plugs.

**Stimulus parameters**

All measurements were performed using the LS CE-Chirp. The stimulus rates were in conformity with the Newborn Hearing Screening Program (2014; see Table 1).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Stimulus rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadband</td>
<td>17.1/s</td>
</tr>
<tr>
<td>Narrowband 1000 Hz</td>
<td>39.1/s</td>
</tr>
<tr>
<td>Narrowband 4000 Hz</td>
<td>49.1/s</td>
</tr>
</tbody>
</table>

For all information about stimulus parameters, see Appendix III.

### 2.4 Analysis

To provide an answer to the first research question, latency data was needed. Consequently, all the latencies of wave I, III and V and all interwave intervals I-III, III-V and I-V of the broadband measurements done in this research (AC and BC measurements, without and with plug), were analysed. First, all raw data points for the four different measurements were plotted and checked for outliers. Outliers were examined on correct identification and reliability by two independent clinicians and, if needed, adapted or removed from the data. Second, all latency data was split...
on gender, since female latencies are significantly shorter than male latencies due to their smaller skull size and thus shorter length of the cochlea (Lotfi & Zamiri Abdollahi, 2012). Subsequently, the analysis was done in two steps, using SPSS. First, a Two-Way MANOVA was carried out, with wave I, III and V as dependent variables, and transducer (AC/BC) and condition (without/with plug) as independent variables. Secondly, another Two-Way MANOVA was performed with the interwave intervals I-III, III-V and I-V as dependent variables and again transducer and condition as independent variables. Both analyses were followed up by simple effects analysis to define the (possible) interaction effect. Additionally, since BC measurements were carried out with the inverting electrodes placed retro- and pre-auricular, an extra analysis was carried out to examine whether the latencies of wave I, III and V and the interwave intervals I-III, III-V and I-V differed between the two electrode positions. Here, the analysis was done in two steps as well. First, an One-Way MANOVA with wave I, III and V as dependent variables and position (retro-/pre-auricular) as independent variable was carried out. Secondly, another One-Way MANOVA with interwave interval I-III, III-V and I-V as dependent variables and position as independent variable was carried out.

To provide an answer to the second research question, threshold data was needed. Consequently, all the PTA thresholds and the thresholds obtained via BERA in the narrowband measurements, at 1000 Hz and 4000 Hz, were analysed. First, all raw data points were plotted and checked for outliers. Simple linear regression analyses were carried out eight times (see Table 2), with PTA thresholds as the dependent variable and BERA thresholds as the independent variable. First, all separate PTA measurements were compared with their resembling BERA measurements. Second, the AC PTA measurements at 1000 and 4000 Hz with and without plug were combined and compared to their resembling BERA measurements, since it is impossible to make a distinction between these two conditions when measuring a patient's ability to hear in clinical practice.

Table 2. Simple linear regression pairs. ‘+’ stands for the ‘with plug’ condition.

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Independent variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTA AC 1000 Hz</td>
<td>BERA AC 1000 Hz</td>
</tr>
<tr>
<td>PTA AC 4000 Hz</td>
<td>BERA AC 4000 Hz</td>
</tr>
<tr>
<td>PTA BC 1000 Hz</td>
<td>BERA BC 1000 Hz</td>
</tr>
<tr>
<td>PTA BC 4000 Hz</td>
<td>BERA BC 4000 Hz</td>
</tr>
<tr>
<td>+PTA AC 1000 Hz</td>
<td>+BERA AC 1000 Hz</td>
</tr>
<tr>
<td>+PTA AC 4000 Hz</td>
<td>+BERA AC 4000 Hz</td>
</tr>
<tr>
<td>PTA AC 1000 Hz</td>
<td>BERA AC 1000 Hz</td>
</tr>
<tr>
<td>+PTA AC 1000 Hz</td>
<td>+BERA AC 1000 Hz</td>
</tr>
<tr>
<td>PTA AC 4000 Hz</td>
<td>BERA AC 4000 Hz</td>
</tr>
<tr>
<td>+PTA AC 4000 Hz</td>
<td>+BERA AC 4000 Hz</td>
</tr>
</tbody>
</table>
3. Results

Typical examples of the BERA measurements for all stimuli are given in Appendix IV.

3.1 Latencies

Two Two-Way MANOVA were used with wave I, III and V or interwave intervals I-III, III-V and I-V as dependent variables, and transducer (AC/BC) and condition (+/-) as independent variables. The data did not meet the assumption of multivariate normality and homogeneity of covariance matrices, so the results should be cautiously interpreted.

Normative latency data of this study was compiled using descriptive statistics (see Appendix V).

Females

Using Pillai’s trace, there was a significant main effect of transducer on the latencies of wave I, III and V: AC measurements showed significant shorter latencies of all waves than BC measurements, \( V = .651, F(3, 37) = 23.015, p \leq .001 \). Using Pillai’s trace, there was a significant main effect of condition on the latencies of wave I, III and V: the condition with plug showed significant longer latencies of all waves than the condition without plug, \( V = .733, F(3, 37) = 33.819, p \leq .001 \). Using Pillai’s trace, there was a significant interaction effect of transducer and condition: the effect of condition on the latencies of wave I, III and V was significantly different for AC measurements than it was for BC measurements, \( V = .801, F(3, 37) = 49.728, p \leq .001 \). Simple effects analysis were done as follow-up. Using Pillai’s trace, for the AC measurements, the condition with plug showed significant longer latencies of wave I, III and V than the condition without plug \( (V = .913, F(3, 37) = 129.786, p \leq .001) \), but for the BC measurements, there was no significant difference in the latencies of wave I, III and V between the two conditions \( (V = .958, p = .423; \text{see Figure 11}) \).

To specify, the latencies of wave I in AC measurements without plug \( (M=1.69, SD=.15) \) were 1.738 ms shorter than the latencies in AC measurements with plug \( (M=3.42, SD=.23) \), \( p \leq .001 \). The latencies of wave III in AC measurements without plug \( (M=3.64, SD=.23) \) were 1.728 ms shorter than the latencies in AC measurements with plug \( (M=5.37, SD=.23) \), \( p \leq .001 \). The latencies of wave V in AC measurements without plug \( (M=5.23, SD=.32) \) were 1.770 ms shorter than the latencies in AC measurements with plug \( (M=7.00, SD=.21) \), \( p \leq .001 \).

There was not a significant difference in the latencies of wave I in BC measurements without plug \( (M=3.10, SD=.52) \) and BC measurements with plug \( (M=2.90, SD=.22) \), \( p = .167 \). There was not a significant difference in the latencies of wave III in BC measurements without plug \( (M=5.25, SD=.42) \) and BC measurements with plug \( (M=5.03, SD=.44) \), \( p = .191 \). There was not a significant difference in the latencies of wave V BC measurements without plug \( (M=7.10, SD=.56) \) and BC measurements with plug \( (M=7.03, SD=.99) \), \( p = .935 \).

Using Pillai’s trace, there was a significant main effect of transducer on the interwave intervals I-III, III-V and I-V: AC measurements showed significant shorter interwave intervals than BC measurements, \( V = .308, F(3, 37) = 5.477, p = .003 \). Using Pillai’s trace, there was not a significant main effect of condition on the interwave intervals I-III, III-V and I-V: the condition with plug did not show significant different interwave intervals than the condition without plug, \( V = .064, F(3, 37) = .839, p = .481 \). Using Pillai’s trace, there was not a significant interaction effect of transducer and condition: the effect of condition on the interwave intervals I-III, III-V and I-V did not significantly differ between AC and BC measurements, \( V = .048, F(3, 37) = .628, p = .601 \) (see Figure 12).
Figure 11. The AC measurements with plug showed significant longer latencies of wave I, III and V than the AC measurements without plug. There was no significant difference in the latencies of wave I, III and V between the two conditions in BC measurements.

Figure 12. AC measurements showed significant shorter interwave intervals than BC measurements. There was no significant effect of condition, nor a significant interaction effect.

Using Pillai’s trace, there was not a significant effect of electrode position on the latencies of wave I, III and V, $V = .108$, $F(3, 8) = .323$, $p = .809$. Moreover, using Pillai’s trace, there was not a significant effect of electrode position on the interwave intervals I-III, III-V and I-V, $V = .197$, $F(3, 8) = .655$, $p = .602$. These results should be interpreted with caution, since $N = 6$. 

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Males
Due to a lack of latency data in males, the statistics that were carried out are not to be interpreted as valid. For more information see Appendix VI.

Table 3 shows the percentage of identifiable and reproducible waves per stimulus for female and male participants together. Broadband measurements were based on 4000 responses. Narrowband measurements were based on 2000 responses.

<table>
<thead>
<tr>
<th>AC</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>70 dB</td>
<td>BB</td>
<td>100%</td>
<td>58%</td>
<td>100%</td>
<td>79%</td>
</tr>
<tr>
<td></td>
<td>(n = 24/24)</td>
<td>(n = 14/24)</td>
<td>(n = 24/24)</td>
<td>(n = 19/24)</td>
<td>(n = 24/24)</td>
</tr>
<tr>
<td>NB 1000 Hz</td>
<td>25%</td>
<td>0%</td>
<td>50%</td>
<td>0%</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>(n = 6/24)</td>
<td>(n = 0/24)</td>
<td>(n = 12/24)</td>
<td>(n = 0/24)</td>
<td>(n = 24/24)</td>
</tr>
<tr>
<td>NB 4000 Hz</td>
<td>83%</td>
<td>21%</td>
<td>87%</td>
<td>54%</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>(n = 19/23)</td>
<td>(n = 5/24)</td>
<td>(n = 20/23)</td>
<td>(n = 13/24)</td>
<td>(n = 23/23)</td>
</tr>
<tr>
<td>40 dB</td>
<td>BB</td>
<td>38%</td>
<td>0%</td>
<td>81%</td>
<td>13%</td>
</tr>
<tr>
<td></td>
<td>(n = 6/16)</td>
<td>(n = 0/15)</td>
<td>(n = 13/16)</td>
<td>(n = 2/15)</td>
<td>(n = 16/16)</td>
</tr>
<tr>
<td>BC</td>
<td>BB (R)</td>
<td>26%</td>
<td>36%</td>
<td>65%</td>
<td>64%</td>
</tr>
<tr>
<td></td>
<td>(n = 6/23)</td>
<td>(n = 8/22)</td>
<td>(n = 15/23)</td>
<td>(n = 14/22)</td>
<td>(n = 21/23)</td>
</tr>
<tr>
<td></td>
<td>BB (P)</td>
<td>33%</td>
<td>n/a</td>
<td>67%</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>(n = 8/24)</td>
<td>n/a</td>
<td>(n = 16/24)</td>
<td>n/a</td>
<td>(n = 22/24)</td>
</tr>
<tr>
<td></td>
<td>NB 1000 Hz</td>
<td>4%</td>
<td>n/a</td>
<td>8%</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>(n = 1/24)</td>
<td>n/a</td>
<td>(n = 2/24)</td>
<td>n/a</td>
<td>(n = 24/24)</td>
</tr>
<tr>
<td></td>
<td>NB 4000 Hz</td>
<td>21%</td>
<td>n/a</td>
<td>58%</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>(n = 5/24)</td>
<td>n/a</td>
<td>(n = 14/24)</td>
<td>n/a</td>
<td>(n = 24/24)</td>
</tr>
</tbody>
</table>

3.2 Thresholds
Simple linear regressions were used to analyse the relation between PTA and BERA thresholds. With simple linear regression analyses, a formula is computed which has the following structure: \( y = a + bx \). In this study, \( y \) stands for the threshold obtained via PTA, \( x \) stands for the threshold obtained via BERA, \( a \) stands for the constant in the formula, and \( b \) stands for the correction factor in the formula; where \( a \) and \( b \) both form the overall correction factor.

PTA AC 1000 Hz – BERA AC 1000 Hz
A simple linear regression was carried out. The correlation coefficient showed a moderate effect when AC PTA thresholds were predicted by BERA thresholds without plug at 1000 Hz, \( R = .77 \). The analyses showed that 56.9% of the variance in PTA thresholds was explained by BERA thresholds, \( F(1, 22) = 31.336, p ≤ .001 \).

BERA thresholds are to be corrected with a value of .597 to predict PTA thresholds (\( B = .597, p ≤ .001 \)). No constant in the function of the correction factor has to be set up (\( B = -1.574, p = .476 \); see Figure 13.a).

PTA AC 4000 Hz – BERA AC 4000 Hz
A simple linear regression was carried out. The correlation coefficient showed a moderate effect when AC PTA thresholds were predicted by BERA thresholds without plug at 4000 Hz, \( R = .78 \). The analyses showed that 59.4% of the variance in PTA thresholds was explained by the BERA thresholds, \( F(1, 22) = 34.584, p ≤ .001 \).

BERA thresholds are to be corrected with a value of .710 to predict PTA thresholds (\( B = .710, p ≤ .001 \)). However, a constant of 4.1 dB should also be incorporated in the function of the correction factor when predicting PTA thresholds by BERA thresholds at 4000 Hz (\( B = 4.105, p = .043 \); see Figure 13.b).

PTA BC 1000 Hz – BERA BC 1000 Hz
A simple linear regression was carried out. The correlation coefficient showed a small effect when BC PTA thresholds were predicted by BERA thresholds without plug at 1000 Hz, \( R = .43 \).
The analyses showed that 14.3% of the variance in PTA thresholds was explained by BERA thresholds, $F(1, 21) = 4.664, p = .043$.

BERA thresholds are to be corrected with a value of .424 to predict PTA thresholds ($B = .424, p = .043$). No constant in the function of the correction factor has to be formulated ($B = 6.130, p = .117$; see Figure 13.c).

**PTA BC 4000 Hz – BERA BC 4000 Hz**

A simple linear regression was carried out. The correlation coefficient showed a moderate effect when BC PTA thresholds were predicted by BERA thresholds without plug at 4000 Hz, $R = .51$. The analyses showed that 22.2% of the variance in PTA thresholds was explained by BERA thresholds, $F(1, 22) = 7.574, p = .012$.

BERA thresholds are to be corrected with a value of .726 to predict PTA thresholds ($B = .726, p = .012$). No constant in the function of the correction factor has to be formulated ($B = 2.524, p = .291$; see Figure 13.d).

**+PTA AC 1000 Hz – +BERA AC 1000 Hz**

A simple linear regression was carried out. The correlation coefficient showed a moderate effect when AC PTA thresholds were predicted by BERA thresholds with plug at 1000 Hz, $R = .59$. The analyses showed that 34.7% of the variance in PTA thresholds was explained by BERA thresholds, $F(1, 22) = 11.679, p = .002$.

BERA thresholds are to be corrected with a value of .520 to predict PTA thresholds ($B = .520, p = .002$). No constant in the function of the correction factor has to be formulated ($B = 1.3670, p = .078$; see Figure 13.e).

**+PTA AC 4000 Hz – +BERA AC 4000 Hz**

A simple linear regression was carried out. The correlation coefficient showed a moderate effect when AC PTA thresholds were predicted by BERA thresholds with plug at 4000 Hz, $R = .78$. The analyses showed that 58.9% of the variance in PTA thresholds was explained by BERA thresholds, $F(1, 22) = 33.955, p = .001$.

BERA thresholds are to be corrected with a value of .854 to predict PTA thresholds ($B = .854, p = .001$). No constant in the function of the correction factor has to be formulated ($B = 1.305, p = .866$; see Figure 13.f).

**PTA AC 1000 Hz – BERA AC 1000 Hz (combined)**

A simple linear regression was carried out. The correlation coefficient showed a strong effect when AC PTA thresholds were predicted by BERA thresholds (without and with plug) at 1000 Hz, $R = .87$. The analyses showed that 74.2% of the variance in PTA thresholds was explained by BERA thresholds, $F(1, 46) = 136.316, p \leq .001$.

BERA thresholds are to be corrected with a value of .797 to predict PTA thresholds ($B = .797, p \leq .001$). No constant in the function of the correction factor has to be formulated ($B = -.2057, p = .424$; see Figure 13.g).

**PTA AC 4000 Hz – BERA AC 4000 Hz (combined)**

A simple linear regression was carried out. The correlation coefficient showed a strong effect when AC PTA thresholds were predicted by BERA thresholds (without and with plug) at 4000 Hz, $R = .92$. The analyses showed that 85% of the variance in PTA thresholds was explained by BERA thresholds, $F(1, 46) = 267.095, p \leq .001$.

BERA thresholds are to be corrected with a value of .801 to predict PTA thresholds ($B = .801, p \leq .001$). No constant in the function of the correction factor has to be formulated ($B = 3.767, p = .052$; see Figure 13.h).
Table 4 shows the correlation coefficients and correction factor that is needed when predicting PTA thresholds by BERA thresholds for all frequencies and conditions.

Table 4. Correlation coefficients and correction factors. ‘p’ stands for the predicted PTA threshold, ‘b’ stands for the obtained BERA threshold.

<table>
<thead>
<tr>
<th>Correlation coefficient</th>
<th>Correction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AC</strong></td>
<td></td>
</tr>
<tr>
<td>- plug 1000 Hz</td>
<td>.77 p = .579b</td>
</tr>
<tr>
<td>- plug 4000 Hz</td>
<td>.78 p = 4.1 + .710b</td>
</tr>
<tr>
<td>+ plug 1000 Hz</td>
<td>.59 p = .520b</td>
</tr>
<tr>
<td>+ plug 4000 Hz</td>
<td>.78 p = .854b</td>
</tr>
<tr>
<td>combined 1000 Hz</td>
<td>.87 p = .797b</td>
</tr>
<tr>
<td>combined 4000 Hz</td>
<td>.92 p = .801b</td>
</tr>
<tr>
<td><strong>BC</strong></td>
<td></td>
</tr>
<tr>
<td>1000 Hz</td>
<td>.43 p = .424b</td>
</tr>
<tr>
<td>4000 Hz</td>
<td>.51 p = .726b</td>
</tr>
</tbody>
</table>

Figure 13. Scatterplots of the relation between PTA and BERA thresholds.
4. Discussion

The first aim of this study was to discern a conductive hearing loss from other pathologies and normal hearing people in otoneurological measurements. The second aim was to examine how BERA and PTA thresholds correlate. Since the two research questions are answered by means of two different analyses, these analyses are discussed separately.

4.1 Latencies

The results of the present study showed that for AC measurements in females, the condition with plug had significant longer latencies of wave I, III and V than the condition without plug; but for BC measurements, there was no significant difference in the latencies of wave I, III and V between the two conditions. This was expected, since the plug creates an obstruction, which causes the auditory signal to reach the cochlea with a decreased intensity. And, the lower the intensity, the longer the wave latencies are. Furthermore, the results showed that there was no significant effect of condition in females on the interwave intervals I-III, III-V and I-V. This was also expected and the results are in accordance with previous findings that AC ABRs of patients with a conductive hearing loss show prolonged latencies of all waves, but no increasing interwave intervals (Fowler & Durrant, 1994; McGee & Clemis, 1982; Rowe, 1978).

The results also showed that, in females, the latencies of wave I, III and V, and the interwave intervals I-III, III-V and I-V were significantly shorter in AC measurements than in BC measurements. These results are in accordance with previous findings that wave V latencies in AC measurements were shorter than those in BC measurements, when performed on the temporal bone (Gorga, Kaminski, Beauchaine, & Bergman, 1993; Mauldin & Jerger, 1979; Yang, Rupert, & Moushegian, 1987). Although the ABRs in these previous studies were evoked by the click as a stimulus, the findings of the present study demonstrate that these results apply to the LS CE-Chirp as well. Yang et al. (1987) explained that the differences in wave latencies between AC and BC measurements results from the fact that bone conducted click stimuli have lower frequency spectral contents and since these frequencies require longer travelling time to reach the apical end of the cochlea, the latencies would have to be longer. However, the current study used the LS CE-Chirp which is designed to compensate for the cochlear travelling wave delay, so the account of Yang et al. (1987) cannot explain the findings of the current study. Since the wave latencies were shorter in AC measurements than in BC measurements in the ABRs evoked by both clicks and the LS CE-Chirp, a more general cause seems to be accountable. Gorga et al. (1993) suggested that there may be some inherent differences between the transmission of energy by AC and BC, but could not explain this. However, the bone conductor may lose some of its energy to other structures than the cochlea. This may be to adjacent bones, but the energy of the auditory signal can also get lost on its way to the cochlea. The part of the cranium beneath the mastoid, where the bone conductor is placed, consists of bone and open spaces filled with air. While the bony parts conduct the auditory signal, some parts of the signal get lost in the open spaces. This causes a loss of intensity, leading to longer wave latencies. Furthermore, Cornacchia, Martini and Morra (1983) not only found that wave latencies in AC measurements were shorter than in BC measurements, but also found that this difference in larger in infants than in adults. However, Cobb and Stuart (2016a) more recently found that, in infants, there was no difference between wave latencies in AC and BC measurements, using both the click and CE-Chirp. For the clinical practice, it is important to know whether AC and BC evoked ABRs can be compared. So, further research should replicate the present study with infants to demonstrate whether the there is a (large) difference in the wave latencies between AC and BC measurements in infants, using the LS CE-Chirp, or not.

Moreover, the results showed that, in females, there was no significant effect of electrode position on the latencies of wave I, III and V nor the interwave intervals I-III, III-V.
and I-V. In addition, there seems to be no considerable difference in success rate between the two electrode positions (see Table 3). These results suggest that the bone conductor can be placed at the position of favour. However, these analyses were done on a small data set (N was 6), so the results should be interpreted with great caution. Speculating about the data, the pre-auricular position seems to be more favourable, since the success rate of wave I is greater than in retro-auricular position. It would be very practical if the bone conductor could be placed on the mastoid in pre-auricular position, since children have small heads which sometime makes it difficult to place both the bone vibrator and the inverting electrode on the mastoid in retro-auricular position. If further research can demonstrate that there is no decrease in the amplitudes of all waves in pre-auricular electrode position, and can confirm that indeed there is no significant effect of electrode position on the wave latencies and interwave intervals, placing the inverting electrode in pre-auricular position may be a solution to evoke BC ABRs in infants.

Unfortunately, there was a lack of male data in this study to perform statistics. However, the data seem to be in accordance with the female data concerning the interaction effect of transducer and condition: in AC measurements, the condition with plug seemed to show longer latencies of wave I, III and V than the condition without plug, and the interwave intervals I-III, III-V and I-V did not seem to be affected by the plug. Speculating about the data, there seems to be a difference in the latencies and interwave intervals between females and males: male wave latencies seem to be longer than those of females. However, a recent study of Cobb and Stuart (2016b) has shown that there is no difference in wave latencies and amplitudes between females and males. No explanation for this finding is given, but it may be due to the fact that Cobb and Stuart (2016b) investigated the effect of gender in infants with the CE-Chirp, while most of the studies that report differences in wave latencies between genders, used adults and the click stimulus. Moreover, the studies that reported on gender differences in infants have been equivocal (Cobb & Stuart, 2016b). Since children are affected by maturation, it is not surprising to see different outcomes between studies. So, further research may acquire more male data to demonstrate whether, in males, the condition with plug also shows longer wave latencies than the condition without plug in AC measurements, and no difference between the two conditions in BC measurements. In addition, a comparison between female and male data should be made concerning wave latencies and amplitudes to check for gender differences. However, not only adult ABRs, but the ABRs of infants should be obtained and analysed as well.

The success rate in Table 3 was calculated for females and males together. First, it showed differences between AC and BC measurements. Waves could be easier identified in AC measurements than in BC measurements, which applies to all waves, stimuli and intensities in the condition without plug; and, in the condition with plug, to all waves and stimuli at 70 dB. This was expected, since BC measurements can only be performed at 40 dB; and, the higher the intensity, the clearer the waves are. So, a transducer that gets to a higher intensity will always have a better success rate. However, in the condition without plug, the same results apply to the comparison at 40 dB. This suggests that AC evoked ABRs are less sensitive to possible interrupting factors than BC measurements. These factors may be transducer placement, the calmness of the participant during the measurements and the fact that, in this study, the BC broadband measurements with plug were always done at last. In addition, although the electrical artefacts of the B81 are a smaller than those of the B71 (Keceli & Stenfelt, 2018), they were more present in BC measurements than in AC measurements. This is due to the fact that a bone conductor is closer to the inverting electrode at the mastoid, having more influence on the recorded signal than inserts have, causing the waves to be less clear or obscured and the success rate to decrease. Only in the condition with plug at 40 dB, the success rate of BC broadband measurements exceeded that of AC broadband measurements at all waves. On
top of that, wave V could always be identified in BC broadband measurements. This finding is of great importance in the clinical assessment of a conductive hearing loss, since the latency of wave V discerns a conductive hearing loss from retrocochlear pathologies.

Second, Table 3 showed differences between the condition without and with plug. As mentioned in section 1.4, the problem in practice with discerning a conductive hearing loss from retrocochlear pathologies is that, in both patients, wave I is not always visible in the ABR due to bad signal-to-noise ratio in the EEG (Fowler & Durrant, 1994; Mackersie & Stapells, 1994). The success rate in Table 3 confirmed this statement, showing that all waves could be easier identified in the condition without plug than in the condition with plug. In the condition with plug, wave I was most difficult to identify, but wave V was identifiable in most cases. It may be expected that wave I is prolonged in patients with a conductive hearing loss, due to the decreased intensity of the auditory signal, but it is not expected to be absent, since having a conductive hearing loss is not a neurological pathology. However, if the auditory signal has largely decreased in intensity, noise may have obscured the presence of wave I. This would implicate that stimulation at a higher intensity should generate wave I. Another explanation could be that there were not enough responses. Although each broadband measurement had 4000 responses, it may not have been enough to bring out wave I.

Third, Table 3 showed differences between broadband and narrowband measurements. Waves could be easier identified in broadband measurements than in narrowband measurements. This is due to the fact that broadband stimuli address the whole cochlea while narrowband stimuli only address a part of the cochlea. So, broadband stimuli cause more nerve fibres to fire synchronously, creating higher amplitudes, which makes it easier to identify the waves. Thus, the success rate was higher for broadband than for narrowband measurements. In the narrowband measurements, it was easier to identify waves in narrowband measurements at 4000 Hz than at 1000 Hz. This is in accordance with the findings of Gorga, Kaminski, Beauchaine and Jesteadt (1988) who evoked the ABRs of normal hearing people using tone burst stimuli. They found that their data was more reproducible for high frequencies than for low frequencies. Gorga et al. (1988) suggest that four factors influence the signal-to-noise ratio. First, the more rapid rise times at high frequencies result in greater discharge synchrony, which in turn results in greater amplitude of the response. However, this first factor does not apply on the results of the present study, since the tone burst is a stimulus with a rise time, a plateau and a fall time, while the LS CE-Chirp, used in this study, does not have a rise time. Second, the nerve fibre density per unit distance is greater at the basal end of the cochlea as compared to higher cochlear turns (Spoendlin, 1972). This increased density results in a greater number of neural elements discharging synchronously for high frequency stimuli. This second factor does apply on the results of the present study, since it is a general characteristic of the cochlea. The synchronous firing of more nerve fibres caused higher amplitudes of the waves which were evoked at 4000 Hz than those evoked at 1000 Hz. Thus, the success rate was higher for the narrowband measurements at 4000 Hz than at 1000 Hz. Third, the more rapid travelling-wave velocity over the basal end of the cochlea results in greater neural synchrony for high frequencies. Since the chirp is designed to compensate for the travelling wave delay, this third factor does not apply on the results of the present study. Finally, phase effects on ABR latencies are most pronounced for stimuli containing low-frequency energy. As a consequence, presenting stimuli with alternating phase could introduce latency ‘jitter’ into averaged responses, and this effect would be greater for low frequencies. This fourth factor also does not apply on the results of the present study, since the polarity that was used, was not alternating, but rarefaction or condensation.

Last, Table 3 showed differences between measurements at 70 dB and 40 dB. In AC broadband measurements, wave could be easier identified at 70 dB than at 40 dB, in all
This study focused on the latencies of the waves and interwave intervals. While wave V amplitudes are of equal value in clinical practice, it was beyond the scope of this study to investigate wave amplitudes. Further research may analyse the data of the present study to demonstrate whether wave V amplitudes are of equal or different size in normal hearing people and patients with a conductive hearing loss.

Furthermore, both the study of Cobb and Stuart (2016b), and that of Lotfi and Zamiri Abdollahi (2012) emphasize the importance of interpreting ABRs using age-based normative data. While normative data for adults has been formulated in this study, further research should obtain the ABRs of infants to create normative data for young children to use in the clinical practice.

4.2 Thresholds
The results of the present study showed that PTA thresholds can be predicted by BERA thresholds. The correlation coefficients can be found in Table 4. First, it showed differences between AC and BC measurements. The correlation coefficients showed a moderate to strong effect (R was between .59 and .92) when AC PTA thresholds were predicted by AC BERA thresholds at different frequencies in multiple conditions, but a small to moderate effect (R was .43 and .51) when BC PTA thresholds were predicted by BC BERA thresholds. This is probably due to larger variety in BC measurements than in AC measurements. The bone conductor should be placed in the exact same position in every participant, so the vibrations are conducted in the same way. However, the size and shape of the head differs per person, so it is difficult to place the bone conductor in the exact same position in every participant. The position of the bone conductor may have differed among participants in this study. This could have led to another transmission of the energy of the bone conductor: other bone structures may have been addressed, leading to a loss of energy by which the cochlea gets stimulated with a lower intensity, this in turn leads to a higher auditory thresholds than is real. When this occurs is some participants, but not all, a lot of variety occurs, leading to a correlation coefficient representing a small effect.

Second, Table 4 showed differences between the measurements at 1000 Hz and 4000 Hz. For all conditions in AC and BC measurements, BERA thresholds at 4000 Hz better predicted PTA thresholds at 4000 Hz than BERA thresholds at 1000 Hz predicted PTA thresholds at 1000 Hz. This is in accordance with previous findings that PTA thresholds are better predicted by BERA thresholds at 4000 Hz than at 1000 Hz (El-Attar et al., 2017; Kestens et al., 2017). Although the ABRs in the study of El-Attar et al. (2017) were evoked the CE-Chirp, the findings of the present study demonstrate that these results apply to the LS CE-Chirp as well. It may be explained by the same theory of Gorga et al. (1988) as was posed in 4.1, that the nerve fibre density per unit distance is greater at the basal end of the cochlea as compared to higher cochlear turns (Spoendlin, 1972) and that this increased density results in a greater number of neural elements discharging synchronously for high-frequency stimuli.

Third, Table 4 showed differences between the condition without and with plug. Overall, BERA thresholds correlated better with PTA thresholds in the conditions without plug than in the condition with plug. This may be explained by the fact that the condition with plug simulates a conductive hearing loss, and that the degree of this hearing loss may have differed between the participants. So, the variety in the condition with plug is greater than in the condition without plug, leading to smaller effect sizes. This variety may also contribute to the fact that the correlation coefficient of the AC measurement with plug at 1000 Hz showed the smallest effect.
of all AC measurements, in combination with a smaller nerve fibre density at the place in the cochlea corresponding to 1000 Hz (Gorga et al., 1988).

Finally, Table 4 showed differences between the separate and combined analyses in AC measurements. The combined BERA thresholds of the measurements without and with plug showed better correlations with PTA thresholds than the separate BERA thresholds without and with plug. This may be explained by the fact that the combined analyses were run on more data, which also makes it more reliable. On top of that, clinicians cannot make a distinction between normal hearing people and patients with a conductive hearing loss in advance, so the strong effect of the correlation coefficients in the combined analyses are promising for the clinical practice.

The results also showed that a correction factor is needed if PTA thresholds are predicted by BERA thresholds, for all frequencies and conditions (see Table 4). These correction factors all showed a positive correction, but were all under 1, meaning that the thresholds obtained via BERA were relatively higher than those obtained by PTA. This may be due to the fact that BERA measurements are very sensitive to residual noise, considering the AEPs are not even 1 µV. Getting closer to the auditory threshold, means getting smaller waves, which are easily overruled by the residual noise. This makes it very hard to get to the true auditory threshold, so a well estimated approach with a correction factor, to overcome the gap between the estimated and the true auditory threshold, is acceptable.

Furthermore, the results showed that no constant in the correction factor had to be formulated, except for the formula that is needed to predict AC PTA thresholds by AC BERA thresholds without plug at 4000 Hz. Here, a constant of 4.1 dB should be added on top of the correction. The fact that adding a constant is only needed for this specific measurement, may indicate a calibration error in the headphones used with PTA at 4000 Hz. However, this finding is not relevant for the clinical practice. Whereas this study could separate normal hearing people from patients with a conductive hearing loss, clinicians cannot make this distinction in advance. For that reason, only the results of the combined data in this study are relevant for the clinical practice.

Since the correlation coefficients of the combined PTA and BERA thresholds in this study represented strong effects, using a correction factor has shown to be meaningful. In an earlier study performed at the Radboudumc, Vonk (2018) found a significant correlation between PTA and BERA thresholds in AC measurements at 4000 Hz, which is in accordance with the findings of the present study. However, the correlation found by Vonk (2018) was a lot smaller (R = .48) than the correlation found in this study (R = .92). Vonk (2018) suggested a simple correction by subtracting 7.9 dB of the BERA threshold to predict the PTA threshold in AC measurements at 4000 Hz, while the present study showed that a more complex corrective formula is needed (p = .801b). Furthermore, Vonk (2018) found no significant correlation between PTA and BERA thresholds in AC measurements at 1000 Hz, but did suggest that BERA thresholds should be corrected with a subtraction of 12.9 dB to predict the PTA thresholds at 1000 Hz in AC measurements. In contrast, the present study did find a significant correlation between PTA and BERA thresholds in AC measurements at 1000 Hz (R = .87) and again formulated a more complex corrective formula (p = .797b). The difference in the findings of the present study and those of the study by Vonk (2018) can partly be explained by the different statistics that were performed. Vonk (2018) found the correlation by calculating Pearson’s R and the correction factor by comparing the thresholds using an ANOVA. So, different analyses were used by Vonk (2018), while the present study put all data in regression analyses, which presents both Pearson’s R and a (possible) correction at the same time.

Dzulkarnain et al. (2017) have investigated the influence of two different electrode montages (ipsilateral: reference to mastoid, and vertical: reference to nape of neck) on the ABR
using the LS CE-Chirp. Their study showed that wave V amplitudes were significantly larger in the ABR recorded from the vertical montage than the ipsilateral montage, while the amplitudes of wave I and III were significantly larger in the ABR recorded from the ipsilateral montage than the vertical montage. Since the inverting electrode in the vertical montage is closer to the origin of wave V (the lateral lemniscus), it is not surprising that these amplitudes are larger than those in the ipsilateral montage. And, since the inverting electrode in the ipsilateral montage is closer to the origin of waves I (beginning of the auditory nerve) and III (cochlear nucleus), it is also not surprising that these amplitudes are larger in the ipsilateral montage than in the vertical montage. Therefore, Dzulkarnain et al. (2017) suggested that the vertical montage should be used in thresholds measurements and the ipsilateral montage should be used in otoneurological measurements. Where Dzulkarnain et al. (2017) only performed measurements with inserts, it is expected that the same results apply to measurements performed with the B81, because there is no difference in electrode montage when using a bone conductor. Besides, it is expected that the electrical artefact may even be smaller in the vertical montage, since the inverting electrode is further away from the bone conductor. However, when using the ipsilateral montage, the electrical artefact of the bone conductor may diminish the positive effect of this electrode montage i.e. obscuring waves I and III. Further research may replicate the present study to compare the electrode montages of Dzulkarnain et al. (2017) in BC broadband measurements and demonstrate whether the expectations as described above are true. In addition, the vertical montage should be used for the threshold measurements to demonstrate whether this electrode montage shows similar or even better correlations with PTA thresholds as observed in the present study.
5. Conclusion

In this study, the additional value of BERA via bone conduction in the clinical assessment of a conductive hearing loss was explored, and the correlation between objective thresholds obtained via BERA and subjective thresholds obtained via PTA was examined.

The findings of the present study confirmed the hypothesis that, in AC measurements, the latency of wave V was prolonged in patients with a conductive hearing loss compared to normal hearing people, while the latency of wave V in BC measurements for both patients with a conductive hearing loss and normal hearing people fell within norm; and that interwave intervals were not affected by a conductive hearing loss.

The findings of the present study also confirmed the hypothesis that BERA thresholds evoked by the LS CE-Chirp can predict PTA thresholds, but that a correction factor is needed. The fact that the combined analyses of BERA thresholds without and with plug at 1000 Hz showed a correlation of .87 and those at 4000 Hz of .92, is very important for the clinical practice. Whereas this study could separate normal hearing people from patients with a conductive hearing loss, clinicians cannot make this distinction in advance. Because of this mixed group wherein clinicians have to discern a conductive hearing loss from normal hearing people, the correction factor of the combined analyses in AC measurements at 1000 Hz (p = .797) and 4000 Hz should be used (p = .801).
References


India. *Indian Journal of Otolaryngology and Head & Neck Surgery*, 1-4. 
https://doi.org/10.1007/s12070-018-1484-3


# Appendix I: Participants

<table>
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<tr>
<th>Participant number</th>
<th>Gender</th>
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<th>Brain damage</th>
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<td>23</td>
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</tr>
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<td>27</td>
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<td>None</td>
</tr>
<tr>
<td>3</td>
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<td>None</td>
</tr>
<tr>
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</tr>
<tr>
<td>5</td>
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<tr>
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<tr>
<td>8</td>
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<td>Right</td>
<td>Reduced hearing</td>
<td>TIA (2004)</td>
</tr>
<tr>
<td>9</td>
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<td>None</td>
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<td>None</td>
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<tr>
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<td>Right</td>
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<td>12</td>
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<td>Tubes during childhood</td>
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<td>Right</td>
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<td>25</td>
<td>Right</td>
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<td>Female</td>
<td>23</td>
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</tr>
<tr>
<td>23</td>
<td>Female</td>
<td>60</td>
<td>Right</td>
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<tr>
<td>24</td>
<td>Female</td>
<td>22</td>
<td>Right</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>
Appendix II: Example BERA-procedure

Step 1  
PTA AC  (L & R)  
PTA BC  (tested ear only)  

Step 2*  
PTA BC  (tested ear only)  
2000 stimuli con 70 dB  
2000 stimuli rar 70 dB  
2000 stimuli con 40 dB  
2000 stimuli rar 40 dB  
BERA AC NB 1000 Hz  (tested ear only)  
1000 stimuli con 70 dB  
1000 stimuli rar 70 dB  
continue threshold measurement with con / rar  
BERA AC NB 4000 Hz  (tested ear only)  
1000 stimuli con 70 dB  
1000 stimuli rar 70 dB  
continue threshold measurement with con / rar  

Step 3*  
BERA BC BB  (retro- and pre-auricular)  
2000 stimuli con 40 dB  
2000 stimuli rar 40 dB  
BERA BC NB 1000 Hz  (tested ear only)  
1000 stimuli con 40 dB  
1000 stimuli rar 40 dB  
continue threshold measurement with con / rar  
BERA BC NB 4000 Hz  (tested ear only)  
1000 stimuli con 40 dB  
1000 stimuli rar 40 dB  
continue threshold measurement with con / rar  

Inserting the plug in the tested ear.  

Step 4  
PTA AC  (tested ear only)  

Step 5  
PTA BC  (tested ear only)  
2000 stimuli con 70 dB  
2000 stimuli rar 70 dB  
2000 stimuli con 40 dB  
2000 stimuli rar 40 dB  
BERA AC NB 1000 Hz  (tested ear only)  
1000 stimuli con 70 dB  
1000 stimuli rar 70 dB  
continue threshold measurement with con / rar  
BERA AC NB 4000 Hz  (tested ear only)  
1000 stimuli con 70 dB  
1000 stimuli rar 70 dB  
continue threshold measurement with con / rar  

Step 6  
BERA BC BB  
2000 stimuli con 40 dB  
2000 stimuli rar 40 dB  

con = condensation polarity; rar = rarefaction polarity; BB = broadband; NB = narrowband  

*Please note that both the order in which the narrowband measurements were performed and whether the measurement started with AC or BC differed between participants.
Appendix III: Parameter settings

<table>
<thead>
<tr>
<th>Stimulation type</th>
<th>BB</th>
<th>NB 1000 Hz</th>
<th>NB 4000 Hz</th>
<th>BB</th>
<th>NB 1000 Hz</th>
<th>NB 4000 Hz</th>
<th>BB</th>
<th>NB 1000 Hz</th>
<th>NB 4000 Hz</th>
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<tbody>
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<td>Stimulus type</td>
<td>LS CE-Chirp</td>
<td>Idem</td>
<td>Idem</td>
<td>LS CE-Chirp</td>
<td>Idem</td>
<td>Idem</td>
<td>LS CE-Chirp</td>
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<tr>
<td>Stimulus rate</td>
<td>17.1/s</td>
<td>49.1/s</td>
<td>17.1/s</td>
<td>49.1/s</td>
<td>49.1/s</td>
<td>49.1/s</td>
<td>17.1/s</td>
<td>49.1/s</td>
<td>49.1/s</td>
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<tr>
<td>Polarity</td>
<td>con/rar*</td>
<td>con/rar*</td>
<td>con/rar*</td>
<td>con/rar*</td>
<td>con/rar*</td>
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<td>con/rar*</td>
</tr>
<tr>
<td>BP-Filter settings EEG</td>
<td>33 – 3000 Hz</td>
<td>Idem</td>
<td>Idem</td>
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<tr>
<td>Number of stimuli</td>
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<td>2x 1000</td>
<td>≥ 2x 1000</td>
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<td>≥ 2x 1000</td>
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<td>Residual noise target line</td>
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<td>Idem</td>
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<td>Rejection level</td>
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<td>Idem</td>
<td>±40 µV</td>
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<td>Idem</td>
<td>±40 µV</td>
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<tr>
<td>Optimize recording</td>
<td>B &amp; M**</td>
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<td>Idem</td>
<td>B &amp; M**</td>
<td>Idem</td>
<td>Idem</td>
<td>B &amp; M**</td>
<td>Idem</td>
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</tbody>
</table>

*con = condensation polarity; rar = rarefaction polarity
** B = Bayesian weighting; M = Minimize interference

- air conduction with inserts
- air conduction with headphones
- bone conduction
Appendix IV: Typical examples

**BB measurements**

BERA AC BB 70 dB (female)

BERA AC BB 70 dB (male)

+BERA AC BB 70 dB (female)

+BERA AC BB 70 dB (male)

BERA AC BB 40 dB (female)

BERA AC BB 40 dB (male)

+BERA AC BB 40 dB (female)

+BERA AC BB 40 dB (male)

BERA BC BB 40 dB (female)

BERA BC BB 40 dB (male)

+BERA BC BB 40 dB (female)

+BERA BC BB 40 dB (male)
NB measurements

BERA AC NB 1000 Hz (female)  
BERA AC NB 1000 Hz (male)  
+BERA AC NB 1000 Hz (female)  
+BERA AC NB 1000 Hz (male)  
BERA AC NB 4000 Hz (female)  
BERA AC NB 4000 Hz (male)
ABR with EMG
## Appendix V: Normative latency data

<table>
<thead>
<tr>
<th>Latencies - Female</th>
<th>- PLUG</th>
<th>+ PLUG</th>
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<tbody>
<tr>
<td></td>
<td>N</td>
<td>MEAN</td>
</tr>
<tr>
<td><strong>AC BB 70 dB</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>19</td>
<td>1.69</td>
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<td>III</td>
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<td>V</td>
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Appendix VI: Results latency data (males)

Two Two-Way MANOVA were performed on the male latency data, with wave I, III and V or interwave intervals I-III, III-V and I-V as dependent variables, and transducer (AC/BC) and condition (+/- plug) as independent variables. However, due to a lack of data and the fact that the assumptions of both multivariate normality and homogeneity of covariance matrices were not met, the results are not to be interpreted as valid.

Due to a lack of (BC) data no analysis could be carried out to examine the main effect of transducer on the latencies of wave I, III and V. Using Pillai’s trace, there was a significant main effect of condition: the condition with plug showed significant longer latencies of wave I, III and V than the condition without plug, for AC measurements ($V = 0.980, F(3, 4) = 66.720, p = \leq .001$). Note: in this analysis no BC data was included. Due to a lack of (BC) data no analysis could be carried out to examine whether there was an interaction effect of measurement and condition on the latencies of wave I, III and V. While no interaction effect was found, simple effects analysis was done as a follow up to specify the effect of condition on the AC measurements. The latencies of wave I in AC measurements without plug ($M=1.73, SD=.08$) were 3.096 ms shorter than the latencies in AC measurements with plug ($M=4.83, SD=1.04$), $p \leq .001$. The latencies of wave III in AC measurements without plug ($M=3.98, SD=.08$) were 2.287 ms shorter than the latencies in AC measurements with plug ($M=6.27, SD=.49$), $p \leq .001$. The latencies of wave V in AC measurements without plug ($M=5.71, SD=.07$) were 2.306 ms shorter than the latencies in AC measurements with plug ($M=8.02, SD=.51$), $p \leq .001$.

Due to a lack of (BC) data no analysis could be carried out to examine the main effect of transducer on the interwave intervals I-III, III-V and I-V. Using Pillai’s trace, there was not a significant main effect of condition: the condition with plug did not show significant different interwave intervals than the condition with plug, for AC measurements ($V = 0.650, F(3, 4) = 2.473, p = .201$). Note: in this analysis no BC data was included. Due to a lack of (BC) data no analysis could be carried out to examine whether there was an interaction effect of measurement and condition on the interwave intervals I-III, III-V and I-V. No follow-up analysis was performed.

Due to a lack of BC data no analysis could be carried out to examine the effect of electrode position on the latencies of wave I, III and V, and the interwave intervals.