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Titel

Hörstyrkefunktion för benlett ljud hos deltagare med rent konduktiv hörselnedsättning.

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Sammanfattning

Bakgrund: Tidigare studier har visat skillnader i hörstyrkefunktion mellan benlett- och luftlett ljud hos normalhörande deltagare. Hörstyrkefunktionen är av stor vikt vid utveckling av preskriptionsregler för hörapparater. Benledda apparater används till stor del av personer med konduktiv hörselnedsättning och kunskap om hörstyrkefunkton i denna grupp saknas.
Syfte: Syftet med denna studie var att jämföra hörstyrkefunktionen för både luft- och benlett ljud hos två grupper av deltagare: 1) med en rent konduktiv hörselnedsättning samt 2) med normal hörsel.
Metod and material: Två grupper inkluderades i studien, en med rent konduktiv hörselnedsättning (N=18) samt en grupp med normalhörande (N=20). En mätning av hörstyrkefunktionen utfördes unilateralt för både luftlett och benlett ljud med hjälp av ”Categorical Loudness Scaling”.
Resultat: Resultaten bekräftade de tidigare studiers fynd av en brantare hörstyrkefunktion när det gäller benlett ljud. Vidare visade resultaten statistiskt signifikanta skillnader mellan de två grupperna, där gruppen med konduktiv nedsättning uppvisade ett mindre dynamikområde samt brantare hörstyrkefunktion än den normalhörande gruppen, både för luftlett och benlett ljud.

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Advanced level

Title

Loudness function for bone conducted sound in subjects with pure conductive hearing loss.

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Abstract

Background: Earlier studies have shown differences in loudness function for bone conducted (BC) - and air conducted (AC) sound in normal hearing subjects. Loudness function is an important factor when developing prescription methods for hearing aids. Bone conducted devices (BCDs) are largely used by people with conductive hearing loss and more knowledge about the loudness function for this group is needed.
Purpose: The aim of this study was to compare the loudness function for AC- and BC sounds in two groups of subjects: 1) a group with a pure conductive hearing loss, and 2) a group with normal hearing.
Method and materials: The study sample consisted of individuals with pure conductive hearing loss (N=18) and normal hearing (N=20). A loudness function measurement was employed unilaterally, for both AC sound and BC sound, using "Categorical Loudness Scaling".
Results: The study results confirm earlier studies findings of a steeper loudness function for bone conducted sound. Furthermore, results show statistically significant differences between the two groups, more specific, the group with conductive hearing loss demonstrated a smaller total dynamic range and steeper loudness function than the normal hearing group, both for AC- and BC sound.

Manuscript

Loudness function for bone conducted sound in subjects with pure conductive hearing loss.

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1. Introduction

1.1. Bone conducted sound transmission

The precise mechanism of bone conduction (BC) hearing is not yet fully understood due to the complexity of co-stimulations where five components are thought to be the most important for BC sound perception; sound pressure in the ear-canal, inertia of the middle-ear ossicles, inertia of cochlear fluids and alteration of the cochlear space (Stenfelt, 2011). In several studies the human skull has been examined through direct stimulation. For example, a model of a human dry skull was made to understand the basic processes of the BC sound (N Kim, Chang, & Stenfelt, 2014). With this model, predictions of the proper BC excitation can be made. Furthermore, the cochlea vibration response has been measured and has shown different movement of the cochlea depending on frequency (Stenfelt & Goode, 2005). In another study made by Stenfelt (Stenfelt, 2007) the famous experiment of von Békésy (1932) when a BC sound was extinguished with an airborne sound was extended. The results indicated that air conducted (AC) and BC sound have a similar effect on the basilar membrane in the inner ear, indicating that the ability to hear a sound is equivalent in both ways. A later study confirmed the previous results concerning the similar effect on basilar membrane with AC and BC sound (N. Kim, Homma, & Puria, 2011).

1.2. Loudness function

Even though both AC and the BC sound seem to affect the basilar membrane in a similar way, there can be differences in how the sound is perceived by the human. According to the Acoustical Society of America Standards (2016), loudness function is defined as the attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from soft to loud. The unit used in describing loudness varies, but one commonly used is "sone", which refers to how loud a sound is perceived (Florentine, 2011). Another unit commonly used is "phon". This unit is used when the loudness is expressed in terms of Sound Pressure Level, SPL, and compared to an equally loud sound (Florentine et.al., 2011). However, loudness function is a subjective estimation and there are no objective methods of loudness measurements. A variation of subjective methods as presented by Stevens (1955) summarizes data from several attempts to measure the loudness function for AC sound subjectively. One example is the method of magnitude estimation, which Stevens found to be the most direct and efficient subjective method of loudness measurement. A more

Ändrad fältkod

contemporary methodology is Categorical Loudness Scaling (CLS) which is standardized in ISO 16832 (2006) and measures loudness over the whole dynamic range. This method has been used and tested in several studies (Rasetshwane et al., 2015; Keidser, Seymour, Dillon, Grant, & Byrne, 1999), it is not time consuming and does not require any training by the subjects involved (Oetting, Brand, & Ewert, 2014), which makes the participants more likely to stay alert during the measurements. The unit used in CLS is categorical units, *cu*. To facilitate comparisons to the more classical measures of loudness, Heeren, Hohmann, Appell & Verhey (2013) have linked the *cu*s to the sones and phons by measuring their relations to one another.

1.3. Loudness for bone conducted sound

Loudness for AC sound has been thoroughly investigated previously (Buus & Florentine, 2002; Moore & Glasberg, 2004), however few studies have examined loudness for BC sound. In one study of BC loudness, Stenfelt and Zeitooni (2013) compared the loudness function for BC stimulated sound with AC stimulated sound in 20 normal-hearing adults. CLS was used and the stimuli for both AC and BC sound were of two types, one low-frequency noise (0.6-0.9 kHz) and one high-frequency noise (3.0-4.0 kHz). The results from this study indicated that the loudness function for BC stimulated sound was steeper than for AC sound, more so with a low-frequency stimulation than with a high-frequency stimulation. Another earlier study showed similar results using a different methodology i.e., a loudness matching of AC and BC sound (Stenfelt et al., 2002). The subjects included in this study had either normal hearing or a mild to moderate sensorineural hearing loss and a difference in loudness function was found between AC and BC sound. The difference was more evident for the low-frequency stimulation.

1.4. Prescription methods

Loudness function is of great importance when developing prescription methods for hearing aids (Moore, 2011; Moore, Alcantara, Stone, & Glasberg, 2009; Moore & Glasberg, 2011; Moore, Glasberg, & Stone, 2009).

A hearing aid prescription is a mathematical formula and it gives the hearing aid preliminary settings, such as suggesting the gain characteristics that are correct for the average hearing-aid user with the indicated hearing loss (Florentine, 2011). Prescriptive methods are based on different rationales but they all are, to some extent, based on loudness considerations.

For air conducted devices (ACDs) there are several prescription methods to choose from, for instance NAL-NL2 (Keidser, Dillon, Flax, Ching, & Brewer, 2011) and DSL v.5.0 (Scollie, 2007), in combination with modified algorithms used by hearing aid manufacturers. According to American Academy of Audiology guideline for the *Audiologic management of the adult patient* (2018) validated fitting rationales in the gain/output in hearing aids are needed, and in addition verification using real-ear measurements (Valente, 2006). For bone conducted devices (BCDs) generally accepted prescription methods have been lacking, as well as objective methods of verification comparable to the real-ear measurements. With these two important components missing in the fitting of the BCDs, reaching the optimal settings are challenging.

Recently a scientific attempt to develop a prescription method for BCDs has been made (Hodgetts & Scollie, 2017) where the findings of steeper loudness function for BC sound shown in the study by Stenfelt and Zeitooni (2013) is taken in consideration. Hodgetts and Scollie (2017) have presented an approach for developing a modified Desired Sensation Level (DSL) algorithm for use with BCDs. However, it has only been evaluated on one sample of experienced users (n=39) of unilateral BCD using one brand of BCD. More work is needed for further validation and utilization in other groups of patients, such as children, users of bilateral BCDs and patients with single sided deafness (SSD). There is also ongoing research in developing a novel bone conduction verification tool using a surface microphone (William, Dylan, Patrick, & Lindsey, 2018). This future opportunity to verify the settings of BCDs along with further work with prescription rules for these devices will help the users to optimize their hearing ability.

1.5. Bone conduction hearing aids

Audiological indications for BCDs include patients with conductive hearing loss or mixed hearing loss. Studies indicate that patients with an air-bone gap of more than 30 dB PTA (Pure Tone Average) of 500-3000 Hz will benefit significantly from BCDs as compared to a traditional air conduction hearing aid (Mylanus, 1998). In addition, SSD may be suitable candidates for BCDs (Flynn, Sammeth, Sadeghi, Cire, & Halvarsson, 2010; Pai et al., 2012). In this case, the sound processor is placed on the poorer ear, and transfers sound to the functioning cochlea.

To ensure personalized prescription as well as best possible outcomes in patients using BCDs more research is required on loudness function in combination with audiological indications. Earlier studies on loudness function for BC sound have included subjects with normal hearing or a mild sensorineural hearing loss which covers only a part of patient groups that can be included in the audiological indications of BCDs (Stenfelt & Håkansson, 2002; Stenfelt & Zeitooni, 2013). Using the methodology of CLS this study intended to add more information about the loudness function for BC sound in one group of BCD users, adult patients with a pure conductive hearing loss.

The primary aim of this study was to measure loudness function for both AC and BC sound in adult subjects with a pure conductive hearing loss and in a control group with normal hearing.

2. Materials and methods

2.1. Subjects

Subjects with pure conductive hearing loss were recruited from databases available at the Region Västra Götaland Hearing Organization. The search was based on the audiological inclusion criteria (for inclusion criteria see below). Letters with an invitation to participate in the study were sent and the volunteers were asked to initiate contact through e-mail or phone. Twenty subjects with hearing loss according to the inclusion criteria accepted to participate in the study. After a pure tone hearing test, two subjects were excluded due to not fulfilling the audiological inclusion criteria. A control group consisting of twenty subjects with normal hearing were also included in the study. The normal hearing participants were obtained through advertisement at the University of Gothenburg campus. All subjects were given oral and written information about the study and all participants gave written informed consent to participate. Movie tickets were offered as compensation for their time. Study subjects were included based on the following criterias:

Subjects with hearing loss:

1. A pure conductive hearing loss in at least one ear

2. Hearing thresholds for BC stimulation equal or better than 20 dB HL at PTA4 (500-, 1000-, 2000- and 4000 Hz)
3. An air-bone-gap equal or larger than 30 dB HL
4. >18 years of age

Subjects with normal hearing:

1. Hearing thresholds for both AC and BC stimulation equal or better than 20 dB HL PTA4 (500-, 1000-, 2000- and 4000 Hz) in at least one ear
2. Normal otoscopy
3. >18 years of age

Exclusion criterion for both groups was a perceived hypersensitivity for loud sounds, about which the participants were asked orally. This criterion was based on the higher-level sounds presented in the loudness function measurement.

All subjects with hearing loss had received hearing rehabilitation using either uni- or bilateral BCDs (N=6), ACDs (N=8) or BCDs on softband (N=4). Demographic data on study subjects is presented in table 1.

Table 1 here

2.2. Test set-up and calibrations

A PC with RME Fireface UC (RME Audio AG, Germany) soundcard generated the test signals. The AC stimulation was presented monaurally through a pair of Sennheiser HDA200 earphones and the BC stimulation, also monaurally, was presented by a B81 bone transducer (Freden Jansson, Hakansson, Reinfeldt, Frohlich, & Rahne, 2017). For the bone transducer, a TDA2003 10x amplifier was used. The output was calibrated with a Brüel & Kjaer 4153 artificial ear in combination with the Brüel & Kjaer 2250 Light Sound Level Meter for the headphones and a Brüel & Kjaer 4930 artificial mastoid for the bone transducer. The distortion level was measured and the maximum stimulation level for the bone conductor was limited to 90 dB HL to ensure low distortion in the stimulation.

2.3. Procedure

All subjects were otologically examined with an otoscope. A pure tone hearing test was performed to ensure the audiological inclusion criteria and thereafter the loudness function was measured using the CLS procedure according to ISO:16832 (2006). The adaptive CLS (Brand & Hohmann, 2002) procedure was applied using the psychophysical-measurement package AFC for MATLAB® developed by Ewert (2013). This software is an implementation of the loudness function fitting according to Oetting, Brand, & Ewert (2014). AFC is a freeware for educational, academic or any non-commercial use.

The subjects were asked to rate presented stimuli on an 11-response scale labeled from *Inaudible* to *Too loud,* as shown in Figure 1. These levels were corresponded to a *cu*-scale from 0 cu to 50 *cu*. All tests were performed at the audiological laboratory at university of Gothenburg.

The scale was displayed on a computer screen and the subjects, seated in a sound proof room, marked the perceived level with the mouse button. The procedure consists of two phases. In the first phase the limits of the auditory dynamic range were estimated by an interleaved ascending and descending stimulus sequence. The first phase in the procedure started with a stimulus at 60 dB HL, both in AC and BC stimulation, thereafter the level was increased by 10 dB until the response *Too loud* was given or the maximum level of 100 dB HL in AC and 90 dB HL in BC was reached. For levels above 90 dB HL, the step size was reduced to 5 dB. The maximum level of 100 dB HL in AC was utilized to avoid harmful levels of sound and 90 dB HL in BC to avoid distortion. In the sequence after, the minimum level of the scale was searched for. The stimulus level was decreased in 15-dB steps until it was inaudible and thereafter it was increased in 5-dB steps until it was audible again. In the second phase, more responses to given stimuli was collected to estimate the different levels of the loudness scale and five labeled levels between *Very soft* (cu=5) and *Very loud* (cu=45) were determined.

According to the ISO standard 16832, 4 frequencies (500 Hz, 1000 Hz, 2000 Hz and 4000 Hz) with narrow band noise were used here. The order in which the stimuli was presented, AC or BC first, was counterbalanced among the participants to avoid bias due to order-effect. Three similar iterations were performed where the first one was considered a training session for the participants to get used to the method. The results from the training session were not included in the data analysis.

Figure 1 here

A loudness model as described by Hohmann and Brand (2002) using the BTPX method (Oetting, Brand & Ewert, 2014) was fitted to estimate the loudness function. According to Oetting, Brand & Ewert (2014) the BTPX method is suggested if data in the upper loudness domain is missing, which is not unusual in CLS measurements. The loudness model consists of two linear parts with independent slope values, k_{low} and k_{high} that are intersected at the level L_{cut}. The estimated slopes are described in cu/dB at low and high stimulation levels. L_{cut} is set at 25 cu and defined as the estimated intersection level between low and high levels.

2.5. Statistics and determination of sample size

N-way ANOVA for repeated measures (AC/BC x NH/HI x frequencies) was performed in Mathworks® Matlab® on the estimated parameters to test for significant differences between means in k_{low}, k_{high} and the dynamic range. The dynamic range was defined as the range between the hearing threshold level (HTL) and the uncomfortable level (UCL) estimated from the CLS measurement. In the cases where the UCL was not reached, the values were extrapolated. A post hoc Tukey test was thereafter used. The level of statistical significance was set at p<0.05. All data was calculated on the two last iterations; the first iteration was only used to train the test person in the methodology.

To achieve 80% power and to detect a difference in dynamic range of 6.2 dB between AC and BC hearing with a one sample t-test with p=0.05, 23 evaluable subjects were needed assuming a within-subject standard deviation (SD) of 10 dB. The expected dynamic range difference and within-subject SD for air- (80.3 dB) and bone (74.1 dB) conducted sounds was related to results presented by Stenfelt and Zeitooni (2013).

The Regional Ethical Review Board (No. 235-17) approved the project.

3. Results

3.1. Loudness functions

The average of the estimated loudness functions for AC and BC stimulation in both NH and the HI group are shown in figure 2. The means of the three parameters k_{low}, k_{high} and L_{cut} are shown in dB HL. Statistically significant effects were seen on k_{low} and the results showed differences between AC and BC sound $F(1)=12.57$, $p<0.05$, between the NH group and HI group $F(1)=326.43$, $p< 0.05$ and between frequencies $F(3)=6.39$, $p<0.05$. A post hoc Tukey test showed the frequency differences being significant between 500-, 1000- and 2000 Hz as well as between 4000-,1000- and 2000 Hz. No significant effects on k_{high} were seen. The inaudible levels, *cu*=0, were lower for the NH group, for both AC and BC sound compared to the HI group. The maximum levels, *cu*=50, were higher for the NH group for AC sound for all frequencies, but the HI group tended to not reach the maximum cu-level due to the output limitations during measurements, and no conclusions can be drawn from these results. For BC sound, the NH group had higher levels for *cu*=50.

Figure 2 here

3.2. The dynamic range

Figure 3 shows the loudness functions for both AC and BC sound for the different frequencies in dB SL where 0 dB SL equals the stimulation level at *cu*=0. According to ANOVA the AC and BC stimulation had no statistically significant effect on the dynamic range but the differences between the groups (NH and HI) and frequencies are statistically significant ($p<0.05$). Post hoc Tukey test showed differences between frequencies 1000- and 2000 Hz compared to 4000 Hz. According to ANOVA the normal hearing group had a larger dynamic range compared to the hearing impaired group, $F(1)=334.65$, $p<0.05$. Within the normal hearing group there were statistically significant differences between AC- and BC sound where the dynamic range for AC sound was larger, $F(1)=73.05$, $p<0.05$. In this group, there were also differences between frequencies, $F(3)=10.77$, $p<0.05$. Post hoc Tukey test showed statistically significant differences between 500- and 4000 Hz for the total dynamic range. The dynamic range for BC sound was smaller for 500- and 4000 Hz compared to 1000- and 2000 Hz. For the group with hearing impairment, differences were seen between AC and BC sound, $F(1) =104.83$, $p<0.05$. Within the HI group the dynamic range was smaller for AC sound, but this group seldom reached the *cu*=50 level for the tested stimuli and therefore the results are not conclusive.

Figure 3 here

Figure 4 shows the dynamic range for both the NH and the HI group, for both AC- and BC sound and for all four frequencies. To eliminate some outliers in the data, the figure shows the 95^{th} percentile. The differences between the two groups and differences in frequencies are statistically significant ($p<0.05$). The NH group had a larger dynamic range for AC sound compared to BC sound and the opposite effect was seen in the HI group, the dynamic range for BC sound was larger than the range for AC sound.

Figure 4 here

Table 3 shows the average k_{low} and k_{high} slopes of the loudness functions in cu/dB. Statistically significant effects were seen on the k_{low} slopes ($p<0.05$). There were differences between the groups, between AC and BC sound and between frequencies. The k_{low} slopes were steeper for the HI group and for AC sound compared to BC sound. Furthermore, the k_{low} was steeper for the frequencies 500- and 4000 Hz compared to 1000- and 2000 Hz. No significant effects on the k_{high} slope could be seen.

Table 2 here

Figure 5 shows the loudness functions for lower levels, the k_{low} slopes for all four frequencies, for both sounds and for both groups. Also in this data, the outliers are removed by using the 95^{th} percentile. The range for the different frequencies is larger for the HI group, which for the AC sound can be explained by the large range in the HTL for this group. The differences between frequencies where 500- and 4000 Hz show steeper k_{low} slopes than for 1000- and 2000 Hz are statistically significant ($p<0.05$).

Figure 5 here

3.3. Differences in loudness functions between the two groups

Results shown in figure 3, table 3 and figure 5 indicated that the HI group had a steeper loudness function for lower stimulation levels for both AC and BC sound through all frequencies (500-4000 Hz). The dynamic range is smaller for the HI group compared to the

NH group, for both AC and BC, see table 2 and figure 4. The smaller dynamic range for AC sound in the HI group is expected since this group did not reach the maximum level *cu*=50.

4. Discussion

The findings in the current study indicate steeper loudness function slopes for lower level sounds for both AC and BC sound for the HI group. This means that for stimuli below the cut point of 25 *cu* in the slopes, the HI group perceived a certain level of sound louder than the NH group experienced it at the same level. Also, the dynamic range was smaller for the HI group for both AC and BC sound but for the AC sound the results are not conclusive.

4.1. Limitations and considerations

The procedure used in this study included the methodology of CLS. CLS has been criticized for the fact that it is an adjectival scale that for computational reasons has been transformed to integers, and the difference between to adjectives like *very soft* and *soft* may not have the same scale difference in loudness as from 1 to 2 (Marks & Florentine 2011). Another issue for discussion is "edge resolution effect". This means that on rating scales like this, participants tend to use the lowest and the highest stimulus level as anchors and they show less variability than responses to levels in between. According to Marks & Florentine (2011) these two factors have consequences when two groups are compared in rating the same scale, for example one group of normal hearing subjects and one group of hearing impaired subjects. A person that barely can hear a sound will probably mark it as very soft which may not necessary be the same experienced loudness that a normal hearing person will mark. In the current study the HTL inclusion criteria for BC sound was the same as for the NH group and should therefore be comparable. However, the HTL for AC sound in the HI group showed a large variety and the maximum level was seldom reached with the consequence of inconclusive results. Further on, modifications have been made, such as the adaptive method of Brand and Hohmann (2002) and the ISO:16832 (2006) standard used in this study. This work with the CLS methodology has helped to ensure reliability and makes it easier to compare studies using this method in a standardized way. Thus, it is a subjective method and comprehensible clear instructions to the participants are very important.
According to a power calculation 23 subjects were needed to be included assuming a within subject SD of 10 dB. Only 18 test subjects could be included within the time frame of this

study. As the found differences are bigger than the values used in the power calculation, the probability of a misinterpretation is very low. Another study with a larger sample size, could help to ensure the results.

The audiological inclusion criteria included PTA4 values. Since it is an average, some individual values differed. For both groups, it could mean that at some frequencies the threshold was over 20 dB HL for bone conduction. For the same reason, the air-bone-gap for the HI group could be smaller than 30 dB HL on individual frequencies. Since this was the occasion for both groups for bone conducted sound, it should not influence the overall results. Concerning the potentially smaller air-bone-gap at a few individual frequencies where the reason being the AC thresholds, the possible effect would be on the AC results for the HI group.

It was noted that the normal hearing group had better bone HTL compared to the group with hearing loss. The HTL has very little effect on loudness functions up to thresholds of 40 dB HL and mostly in the higher levels (Smeds & Leijon, 2011). The results showed statistically significant differences in the lower levels so these differences should have no or a small effect.

Few test subjects responded the highest level of response on the categorical loudness scale (50 *cu*), mainly on BC sound due to the maximum level of 90 dB HL which was used to avoid distortion. Consequently, not much data was collected on loudness functions for higher level sounds and no conclusions can be drawn here.

4.2. Comparison with earlier studies

Some of the current results are comparable with the results shown in the study by Stenfelt and Zeitooni (2013) as well as in the earlier study by Stenfelt and Håkansson (2002). The subjects in Stenfelt and Zeitoonis study (2013) were normal hearing and the results showed an average low-level slope of the loudness functions for AC sound of 0.45 cu/dB for both low and high frequencies, of 0.52 cu/dB for low-frequency BC simulation and of 0.50 cu/dB for the high-frequency BC stimulation. In this study, average k_{high}, the high-level slope, was 0.92 cu/dB for the low-frequency AC stimulation, 0.98 cu/dB for the high-frequency AC stimulation, 1.02 cu/dB for the low-frequency BC stimulation, and 0.99 cu/dB for the high-frequency BC stimulation. Compared to current data the slopes are steeper than reported by Stenfelt and Zeitooni (2013) for both AC and BC sound for k_{low}, a difference around 0.17-0.21

cu/dB, but less steep for k_{high}, a difference around 0.54-1.51 cu/dB. The stimuli used in the measurements differ between the two studies. In the current study four frequencies of narrow band noise were used (500-, 1000-, 2000- and 4000 Hz), whereas in the study by Stenfelt and Zeitooni (2013) two frequencies were used; one low-frequency noise (0.6 to 0.9 kHz) and one high-frequency noise (3.0 to 4.0 kHz). This may have caused the differences in the results.

Even though the numbers differ, the results showing the steeper loudness function for BC sound are similar. Results in the earlier studies (Stenfelt & Zeitooni, 2013; Stenfelt & Håkansson, 2002) indicated that the steeper loudness was more evident for low frequencies. The current study confirms that for 500 Hz, but also indicate that the slopes are steeper for 4000 Hz compared to 1000 and 2000 Hz. These new results suggest that future work with prescription rules for BCDs should not only consider the steeper loudness function for lower level sounds in the lower frequencies, but also for the higher.

Results for the dynamic range shown by Stenfelt and Zeitooni (2013) was 81.2 dB (AC) and 71.4 dB (BC) for low-frequency sound and 80.3 dB (AC) and 74.1 dB (BC) for high-frequency sound. The dynamic range in the current study showed larger numbers for the normal hearing group, mean for all frequencies for AC sound was 110.8 dB and for BC sound 96.0 dB, but the smaller dynamic range for BC sound is the same. The larger dynamic range in current study may be explained by the choice of extrapolating the UCL when the maximum level of the loudness scale was not reached.

The measurement of CLS according to the ISO:16832 (2006) is the same in both studies and makes the results comparable. The number of subjects in both studies are similar but there are some differences in the methodology and design of the two studies, for instance, differences in age between the two groups. The HI group in the current study was notably older than the NH subjects and the participants in the study by Stenfelt and Zeitooni (2013). Age influences the function of hearing, for example the mechanism in the cochlea. The HI group fulfilled the audiological criteria of HTL equal or better than 20 dB HL for BC sound, and therefore should the age difference have no effect on the results. Older age brings cognitive decline, but in ages below 65 years the effect is very small (Cornelis et al., 2019), and the mean age in the NH group was 51. Also, the task in the CLS measurement does not require any higher cognitive skills. Another difference between the two studies is how the stimuli was presented. In the current study the stimuli was presented unilaterally both for AC and BC sound but in the study by Stenfelt and Zeitooni (2013) the stimuli were presented bilaterally. While this difference may affect the results due to the loudness summation effect, several studies have demonstrated that the stimulation level has minimal influence on the binaural loudness summation (Sivonen, 2006). If so, it is more evident for high level stimuli.

In addition, different bone transducers were used. In this study B81 was used, instead of B71 that was used by Stenfelt and Zeitooni (2013) with a balanced technology that reduced distortion. According to Jansson et al (2015) the B81 has advantages of having lower distortion and therefore allows higher hearing levels than the B71 below 1500 Hz.

4.3. Differences in loudness function for AC and BC sound

Possible reasons for the different loudness functions for AC and BC sound is mentioned in the study by Stenfelt and Zeitooni (2013). The acoustic reflex influences the sound transmission, but mainly for the higher levels of stimuli and does not explain the differences in the lower levels. For the same reason, multi-sensory loudness integration is ruled out as an explanation. The tactile sensation of the vibrations from BC sound can affect in such way that the perception of the sound feels louder and the participant indicates a higher grade of loudness, but only on higher levels (Stenfelt et al., 2002).

4.4. The protected cochlea

Studies have shown that conductive hearing loss has a degenerating effect on the cochlea (Liberman, 2015), on the auditory nerve (Zhuang, Sun, & Xu-Friedman, 2017) and on the auditory cortex (Xu, Kotak, & Sanes, 2007). It has also been speculated that the blocking in the outer or the middle ear reduces the sound energy to the cochlea and therefor has a protective effect, but very little research has been done in this area. In one such example, a study was made on workers in a noisy environment where the subjects with a conductive hearing loss showed better hearing thresholds than subjects with no conductive hearing loss (Park, 2016). The group had hearing aids but the sound reaching the cochlea will not be as loud as for a normal hearing person. It may be possible that this protection of the cochlea also brings a higher sensitivity to sound and therefor a steeper loudness function for BC sound in this group.

4.5. Clinical applications

Earlier studies have already indicated different loudness function for AC and BC sound and the results have been applied in an attempt of developing prescription rules for BCDs. These current results indicate that even though the cochlea is undamaged, the loudness function is steeper for lower level sounds and the dynamic range is smaller in subjects with pure conductive sound for BC sound, compared to normal hearing subjects. This may be important to consider in the following work of prescription rules and fitting of the bone conducted devices, more specifically for the lower level sounds in both lower and higher frequencies. More work is needed to map the loudness function for BC sound in other groups that are users of BCDs, for example persons with mixed hearing loss. More knowledge of BC sound will make the BCDs more accurate in the fittings and benefit the users in their ability of hearing and in the sound comfort.

5. Conclusion

The loudness function was significantly steeper for low-level sound for the HI group, for both AC and BC sound. The dynamic range was smaller for the HI group and there were statistically significant differences between AC and BC sound within the groups. For the NH group the dynamic range was larger for AC sound which is similar to the results reported by Stenfelt and Zeitooni (2013). Same method was used in the two studies even though there were some differences, for example different stimuli.

An explanation to the steeper loudness and smaller dynamic range for BC sound in the HI group could be the protected cochlea.

These findings show that loudness perception clearly differs between normal hearing subjects and subjects with a pure conductive hearing loss. The steeper loudness function is important to consider in the work with developing prescription rules for BCDs, and in the clinical work with these patients.

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Table 1. Demographic data on study subjects. PTA4 is shown for air and bone conduction sound for the test ear.

		Age, years	PTA4 air, dB HL	PTA4 bone, dB HL
Normal hearing	Mean	30	2	2
N=20	Median	27	2	2
Male 6	Standard Deviation	8	4,6	3,8
Female 14	Min-Max	21-50	-4-13	-4-10
Hearing impaired	Mean	51	54	14
N=18	Median	55	53	14
Male 8	Standard Deviation	15	11,4	5,0
Female 10	Min-Max	20-71	33-76	1-20

PTA4= Pure-tone average 500-, 1000-, 2000- and 4000 Hz.

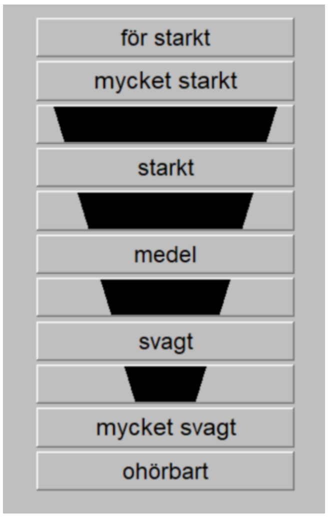

Fig. 1. The scale used in Categorical Loudness Scaling (CLS). The picture is taken from the actual measurement used in the study and therefor in Swedish. The subjects were asked to mark the perceived loudness after each stimulus, from *inaudible* (‘ohörbart’) in the bottom to *too loud* (‘för starkt’) in the top of the scale.

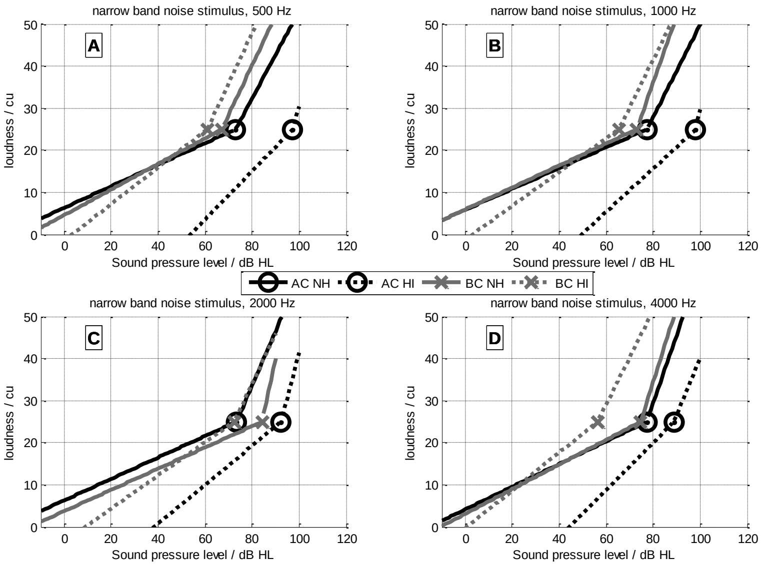

Fig. 2. Loudness functions from the CLS (categorical loudness scaling) measurement for both groups, normal hearing (NH) in black and hearing impaired (HI) in grey at four different frequencies (A-D). The loudness functions are based on means for k_{low}, k_{high} and L_{cut}. Air conducted (AC) sound is shown in a solid line and bone conducted (BC) sound in a dotted line. Statistically significant differences are seen for k_{low} between AC and BC sound, between the two groups and between frequencies 500/4000 and 1000 Hz as well as 500/4000 and 2000 Hz.

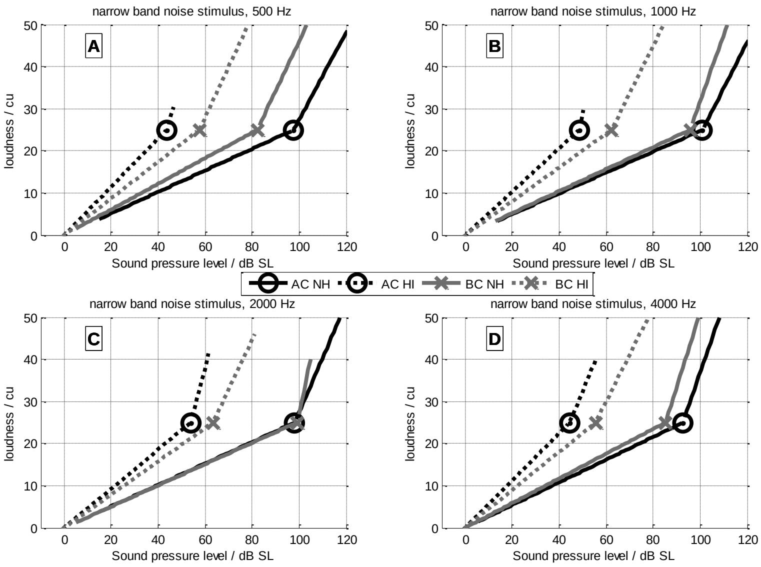

Fig. 3. The loudness functions based on the averaged parameters k_{low}, k_{high} and L_{cut} in sensation level for all four frequencies (A-D). The AC (air conducted) stimulation is shown in black and BC (bone conducted) in grey. The results for the NH (normal hearing) group is shown with a solid line and the results for the HI (hearing impaired) group with a dotted line. L_{cut} is marked with a ring and with a x, the line below is k_{low} and the line above is k_{high}. Maximum stimuli for AC sound was 100 dB HL and for BC sound 90 dB HL.

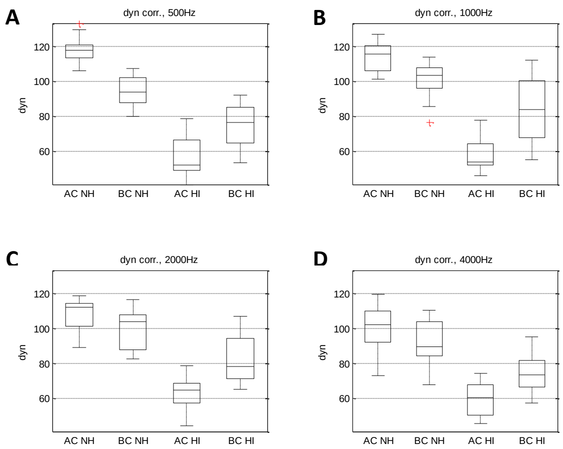

Fig. 4. The dynamic range, the difference between the estimated UCL (uncomfortable level) and HT (hearing threshold), for both groups, both AC (air conducted) and BC (bone conducted) sound and for all four frequencies (A-D). The NH (normal hearing) group has a larger dynamic range for AC sound compared to BC sound and the HI (hearing impaired) group has a larger dynamic range for BC sound compared to AC sound. These differences as well as the effect of the different frequencies are statistically significant.

Table 2. Average low level and high level slopes, cu/dB, for both the NH (normal hearing) and the HI (hearing impaired) group and for both AC (air conducted) and BC (bone conducted) sound.

Stimulation	Group	Frequency, cu/dB							
		500 Hz		1000 Hz		2000 Hz		4000 Hz	
		k_{low}	k_{high}	k_{low}	k_{high}	k_{low}	k_{high}	k_{low}	k_{high}
AC	HI	0.59	2.55	0.51	2.88	0.50	2.78	0.58	1.93
	NH	0.26	1.46	0.24	1.94	0.26	1.84	0.28	2.27
BC	HI	0.46	1.25	0.39	1.45	0.40	1.59	0.46	1.28
	NH	0.31	1.89	0.28	2.26	0.27	3.19	0.31	2.50

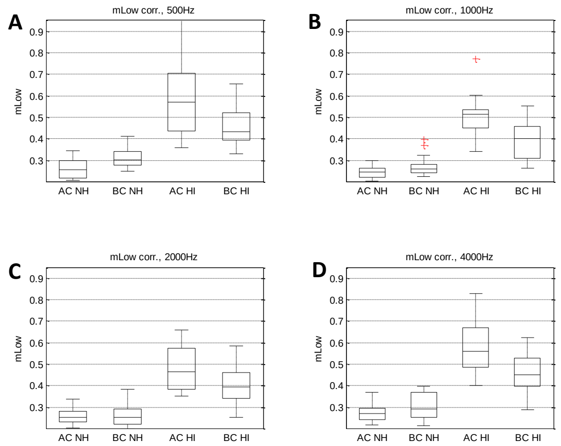

Fig. 5. Results for k_{low}, the loudness function for lower levels, for all four frequencies (A-D), for both AC (air conducted) and BC (boned conducted) sound and for both the normal hearing group and the hearing impaired (HI) group. Results is shown in cu (categorical units)/dB.