On Bone Conduction Hearing Perception and Equalisation Methods for Bone Conduction Headphones

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Abstract

Bone conduction headphones have recently been introduced in the commercial market; however, the study of bone conduction hearing perception can be traced back to the early 20th century. This paper discusses the mechanics of bone conduction hearing perception in detail, with special attention devoted to the various factors which affect hearing perception in bone conduction systems. The paper also discusses existing equalisation methods utilised for bone conduction headphones, as the equalisation function for such devices defers greatly from air conduction headphones. Additionally, potential future methods of equalisation are put forward for future studies to explore.

1 Introduction

Bone conduction (BC) headphones have been used historically in the field of technical audiology to restore hearing in cases of conductive hearing loss. This technology was then adopted by in military applications, due to its advantage of transmitting sound to the listener while still permitting the perception of ambient sound. In the 21st century, this technology has been incorporated in headphones available in the commercial market; however, the perception of BC transmitted sound is still being debated by contemporary academics [1, 24].

The primary difficulty in study of BC hearing perception is the numerous factors that affect it. In BC transmission, sound is transmitted via a vibrating unit that is placed against the skin of the listener's skull. This unit transfers the sound signal in the form of vibration to the skull, from where the signal can travel to the cochlea as well as the cerebro-spinal fluid (CSF) [25]. Thus, in contrast to air conduction

(AC) transmission of sound which has limited pathways, sound can travel through multiple pathways in BC transmission [26]. Other factors, such as the individual's physiology and specifications of the vibrating unit also affect the sound perceived by the listener [23, 17].

As this mechanism makes little use of the ear canal, equalisation for BC headphones differs from that of AC headphones. The ear canal resonances have little relevance in this scenario, while the resonances of an individual's skull has a significant amount of importance. Additionally, the nature of the impedance of the skull in conjunction with the inertia of the various fluids present within it has detrimental effects on sound transmission, particularly in the higher frequencies [15].

This paper presents a literature review of the mechanism of bone conduction hearing perception, as well as a discussion of the existing equalisation methods for BC headphones. In addition, two potentially new methods of equalisation are proposed in this paper; however, due to a lack of resources, only the hypotheses are presented. It is hoped that these hypotheses are investigated and expanded upon in the future.

The structure of this paper is as follows. Section 2 is a discussion of the intricacies of BC hearing perception. This is followed by Section 3, which explores the existing methods of BC headphone evaluation. Section 4 then proposes potential other methods of BC headphone equalisation. The paper is then concluded in Section 5, the conclusion.

2 Mechanism of BC Hearing

Bone conduction headphones operate by vibrating the skull via a vibrating transducer. These vibrations are coupled to the bony labyrinth of the cochlea, causing the labyrinth to vibrate. This in turn sets the fluid of the cochlea in motion, which is picked up by the outer and inner hair cells. There are several products based on BC which are commercially available today; however, the details of BC acoustics are still a matter of debate. While several studies have investigated the mechanics of BC hearing using cadavers or subjects with BC implants, the intricacies of the BC auditory pathway is not well understood [20].

A major contributor to the complexity of BC hearing is that sound travels through multiple pathways to reach the basilar membrane. These pathways are difficult to isolate due to the interactions between them. Figure 1 displays a diagram a theorised model of the BC pathways by Stenfelt [24]. This model displays the effects of a BC vibration against the skin of a subject's skull and the AC sound of the subject's own voice. In the most direct pathway, the vibrations pass through the skin, to the skull bone. These vibrations are then transformed into pressure waves in the cerebro-spinal fluid (CSF), which then travel to the fluid in the inner ear. It should be noted that the AC sound entering the ear canal in this diagram of the model is the sound of the subject's own voice and not AC sound from the BC vibrator [24].

Of particular note in figure 1 is the various interactions between the various components of the BC auditory path and the traditional auditory path. The vibrations in the skull, and to some extent the skin, produce pressure variations in the ear canal. These pressure vibrations can be coupled to the typanic membrane and transmitted along the traditional pathway of AC sound. The sound transmitted in this manner is termed as skull vibration induced AC sound. The contribution of this sound to the overall BC sound perception is considered to be less than that of the other components in the model. Steinfelt stated in [29] that this component contributed 10 dB fewer than other components at lower frequencies and the contribution was negligible at higher frequencies. The position of the transducer also affects the magnitude of contribution, as transducers placed close to the ear canal increase the contribution for lower frequencies [29].

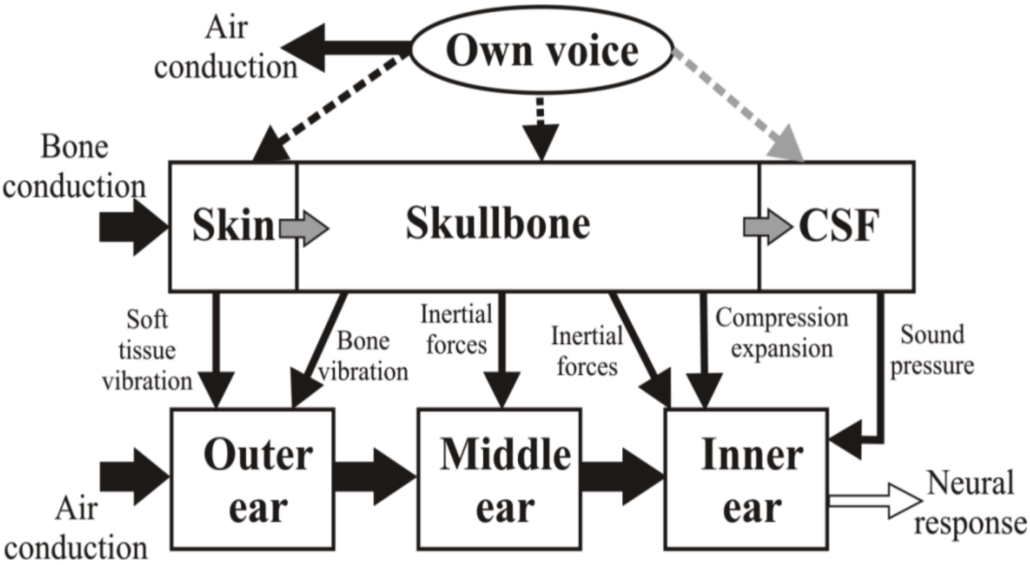

Figure 1: Pathways in conduction of sound in BC hearing. Adopted from [24].

All the components which contribute to BC hearing perception are not linear. BC hearing can, therefore, be considered as a complex interaction of linear and non-linear systems. At frequencies up to 10 kHz, BC hearing can be considered linear [10, 11, 8]. However, there is evidence of non-linearities in the signal that has been found by several studies [2, 14]. The linearities and non-linearities may be due to a number of factors. These factor include include the sound level at the external ear canal, the inertia of the ossicles, the cochlea compression, the transmission of pressure waves in the cerebro-spinal fluid (CSF), the change in cochlear space, and the inertia of the fluid in the cochlea [26, 5].

Of the above listed factors, the last two are considered to be the most important to BC hearing perception [25]. It is theorised that measurement of cochlea vibration is method of estimating BC hearing perception; however, several studies that looked into the relationship between hearing thresholds and cochlea vibration could not find a strong correlation between them [27, 7, 6, 21]. This can be problematic for proposed methods of equalisation that use hearing thresholds to derive the equalisation function.

Another factor which can affect BC hearing perception is the position of the BC vibrating unit, a fact which was noted earlier in the BC hearing perception model. Studies that have compared the performances for several different positions of the vibrating unit have concluded that the mastoid had the lowest BC hearing thresholds and the forehead the highest BC hearing thresholds [30, 9]. Another study concluded that the head of the mandible is the most conducive to BC hearing perception, as placement there produced the lowest BC hearing thresholds [18]. It should be noted that the difference in speech perception is negligible, whether placement is on the mastoid or on the head of the mandible. Some actuators are placed within the ear canal; however, this is more in the case of hearing aids and not headphones [24].

Finally, the individual subject's head geometry and density can also influence BC hearing perception. BC hearing can be highly individualistic due to these factors. Each skull shape affects the propagation of sound as there are different resonances induced in individuals due to their skull shape [4, 13]. Bone density affects the impedance of the skull, which in turn affects the quality of the sound [20, 2]. Additionally, age and temperature can affect skull impedance [4].

In comparison to AC hearing perception, the frequency range of BC hearing perception can be quite limited. Above 10 kHz, BC sound is significantly attenuated [23, 20]. Clinically, BC threshold tests are rarely administered for frequencies above 4 kHz [4, 23]. The mass-inertia characteristics of BC systems adversely affect the conduction of sound at higher frequencies [23]. The difference in conduction at higher frequencies manifests itself as a difference in loudness perception between BC and AC sounds. This may be due to the non-linearities in the BC pathways, which cause distortion in the perceived sound signal [28]. There is also a possibility that sounds present in frequencies that are typically out of the audible frequency range are shifted, in a manner that they are perceivable to humans [28].

The difference in transmission between AC and BC sound can be seen in the processing for bone anchored hearing aids. In typical hearing aids, which transmit sound via AC, a gain of 5 dB is insufficient for the user to perceive sound; on the other hand, for bone anchored hearing aids such a gain is ample for perception [32]. This difference in required gain is more prominent at lower frequencies. One study found that it ranges from 6 dB to 10 dB for the frequency range 250 Hz to 750 Hz, while for the frequency range 1 kHz to 4 kHz the difference is only 4 or 5 dB [23].

The relative difference in BC and AC hearing perception can be seen in figures 2, 3, and 4, which display the normalised results of hearing threshold measurements that were measured relative to AC transmitted sound at sound level at 40 dB and 60 dB in an experiment which investigated the relationship between BC loudness perception and acceleration of the skull during BC excitation [20]. The results are

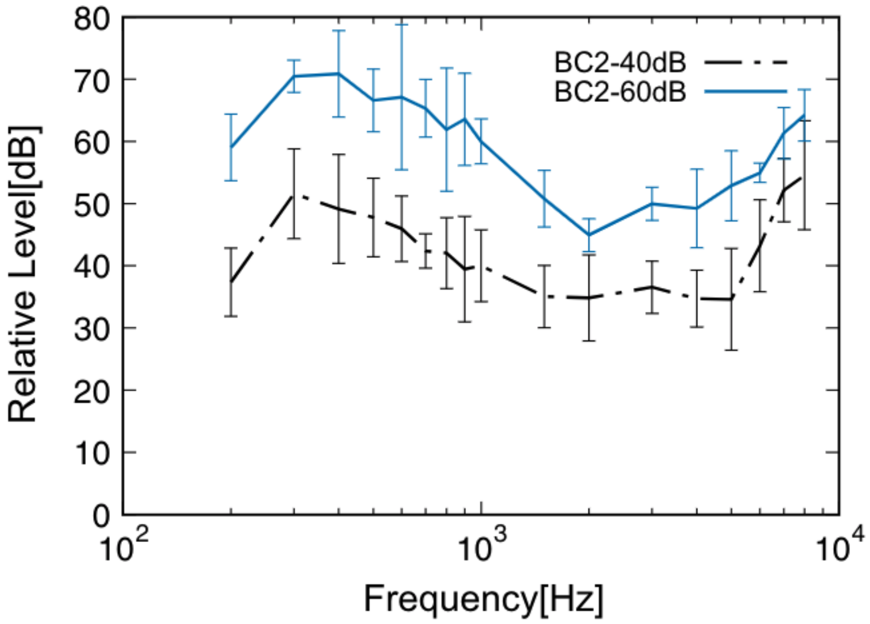

Figure 2: Loudness measurement of BC transducer with vibrating surface area of $133mm^2$, relative to AC sound samples. Adopted from [20].

normalised with respect to the 1 kHz point; The 'y' axis is therefore labelled as 'Relative Loudness'. The experiment measured the loudness perception across four different transducers, one of which has been omitted here as that transducer was positioned inside the ear canal. The other three BC transducers were placed at the head of the mandible of the subjects [20]. The relationship between vibrating unit surface area and BC hearing perception is illustrated in the figures.

It is also interesting to note that effective vibrating surface area plays a role in BC transmitted loudness perception. BC-4 has the smallest vibrating surface area and the largest differences in AC and BC loudness perception. Also of note is that the entire surface area of the vibrating unit does not translate to effective vibrating surface area, as in the case of BC-3 in figure 2, the surface area of the vibrator is quite large, but the relative loudness levels are not ideal. This may be due to the fact that in this instance the entire surface area of the vibrating unit was not in contact with the skin of the subjects [20]. It may also be due to the fact that the larger the vibrating unit, the more power consumed by the unit.

In general, it may be said that BC headphones perform inadequately when transmitting audio when compared to AC headphones. The signal perceived via BC has been described as muffled and poorer in quality when compared to playback through normal headphones or through loudspeakers [15]. While this may be due to a number of reasons listed here, i.e. the limited frequency range, the non-linearities present in the signal, the affect of an individual's skull geometry and density, it must be noted that primarily, most acoustic recordings are created with the traditional

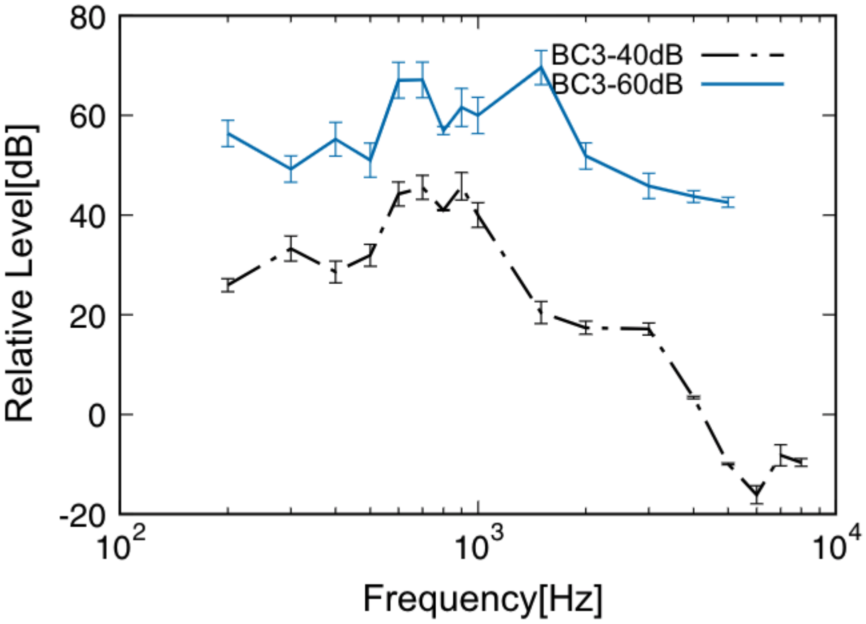

Figure 3: Loudness measurement of BC transducer with vibrating surface area of $440mm^2$, relative to AC sound samples. Adopted from [20].

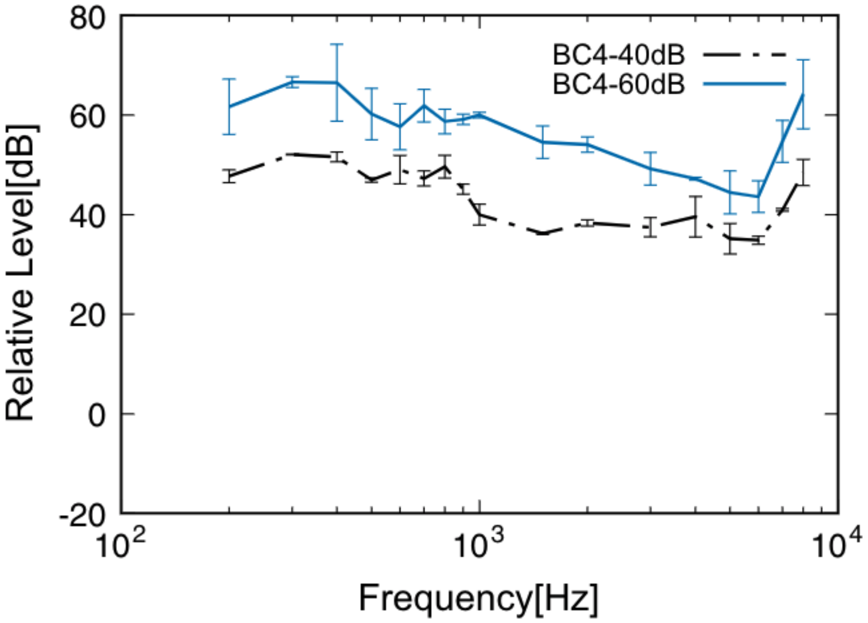

Figure 4: Loudness measurement of BC transducer with vibrating surface area of $70mm^2$, relative to AC sound samples. Adopted from [20].

air transmission path in mind. Therefore, these recordings are not well suited to bone conduction headphone playback, which contributes to the poor audio quality. Furthermore, stereo bone conducting headphones have the additional problem of cross-talk, which is nigh impossible to counteract as that would require isolating the two cochlea from each other.

3 Current Equalisation Methods

Due to the number of factors which affect BC hearing perception, equalisation of BC headphones is a challenge. The earliest equalisation method was one proposed in 1950 by Carhart [3], who derived a correction factor from the results of listening tests involving normal hearing subjects and subjects with hearing loss. This method of equalisation was used in clinical test until the development of sophisticated artificial mastoid models, at which point it was possible to take more accurate measurements of BC transmission [4]. Clinics were then able to attach the vibrating unit to a mastoid model and match the impedance values measured by Wilbur in 1972 [33] and included in ANSI standards. These values later updated for contemporary mastoid models in more recent ANSI standards. However, a major drawback of this calibration method is that the frequency range is limited to 0.25 kHz to 4 kHz due to the high number of non-linearities and other factors of BC hearing perception that are not accounted for in the mastoid models [24]

Few publications of listening tests involving BC headphones list the equalisation method that was utilised, or even if equalisation was performed at all. However, the author has found a few publications which mentioned their equalisation method.

In [22], a study comparing headphone performance for virtual sound source localisation, equalisation was performed based on frequency responses obtained from the manufacturer. This method was also utilised in [17], which was as study of spatial audio via BC headphones. Figure 5 displays the frequency responses of the BC headphones that were involved in the study. These responses were presumably obtained utilising a dummy head. This method is not individualistic and, if measured using a dummy head or mastoid model, may not account for non-linearities.

A different equalisation method was utilised by [16], which studied spatial audio via BC headphones for augmented reality purposes. This method of equalisation was a psychoacoustic method in which each subject in the study was asked to compared sound reproduced via loudspeakers to the sound perceived via the loudspeakers. This was done for a number of frequency bands until the BC headphones were adequately equalised. Unlike the previous methods, this equalisation method caters to an individual.

Another method of equalised was put forward and patented Heiman et al. [12]. In this method, two BC elements and a digital processing unit are required. One BC unit is the vibrating headphone unit, which is positioned on the mastoid. The other

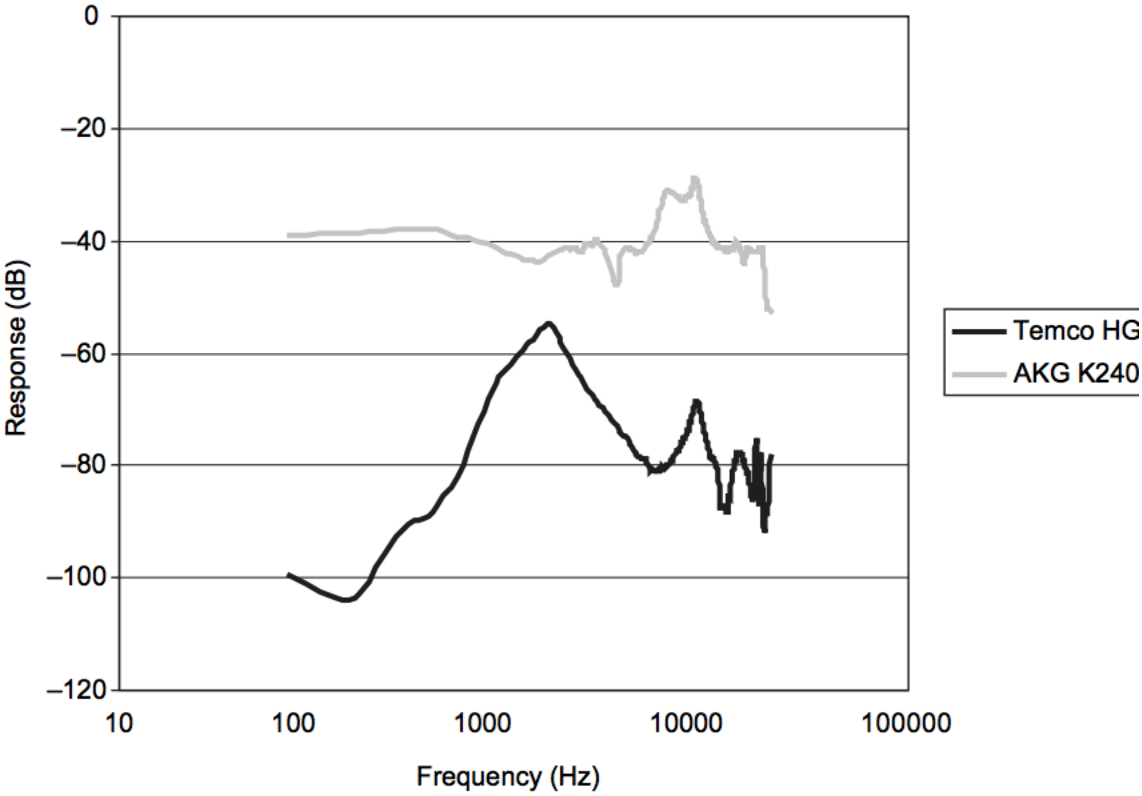

Figure 5: Frequency responses of two BC headphones:the Temco HG-17 bone vibrator and the AKG K240DF Adopted from [17].

BC unit is a microphone unit, which is positioned on the temporal bone. Equalisation is performed in the digital processing unit based on the feedback from the BC microphone unit. Such a system is expensive due to extra hardware required, so it undesirable. Additionally, BC microphones have limited frequency range due to the mass-inertia system of the skull affecting higher frequencies [15, 24]. Furthermore, it may be argued that such a system is not a true measure of the perceived signal as the change in cochlea space, the inertia of the cochlea fluid, and the affect of the CSF are not measured in this system. As stated earlier, these are important contributors to BC hearing perception and are are likely the cause of non-linear distortion in the perceived signal [24].

Another, more mathematical method was put forward Tang et el [31], who proposed a method of equalisation in which the transfer function for the bone-air differential was utilised to create an equalisation filter. It should be noted that in this work the BC vibrating unit was placed against the temporal bone and not the mastoid. The transfer function was calculated utilising hearing thresholds, in a manner which accounted for the difference between AC and BC hearing perception.

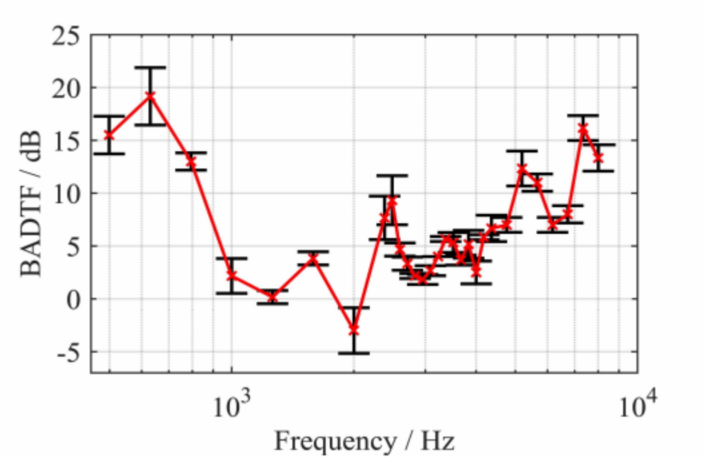

Figure 6: Calculated BADTF for one subject. The mean and standard deviations over three measurements are displayed. Adopted from [31]

The bone-air differential transfer function (BADTF) calculated in [31] was:

$$BADTF(f) = 20lg|\frac{E_B^{HT}(f)}{E_A^{HT}(f)}|, \tag{1}$$

in which $E_B^{HT}(f)$ and $E_A^{HT}(f)$ are the putout signal from BC and AC headphones, respectively, when they are equivalent to the BC and AC hearing thresholds, respectively [31].

The BADTF can be used to calculate an equalisation filter using the following equation:

$$BADTF(f) = 20lg|H_{eq}(f)|, \tag{2}$$

in which $H_{eq}(f)$ is the equalisation filter [31].

The hearing threshold measurements were performed in an anechoic chamber and utilised AC and BC headphones. The BADTF was then calculated utilising equation 1. Figure 6 displayed the calculated BADTF for one subject who participated in the study [31]. The figure clearly displays the attenuated higher frequencies which are typical of BC audio.

The calculated BADTFs were used to derive individual equalisation filters for the test subjects. A listening test was then performed, in which the test participants were asked to compare samples played over the unequalised and the equalised BC headphones to samples played over AC headphones [31]. The comparison was done on a scale of 1 to 5, with 1 being completely unlike the AC samples and 5 being exactly like the AC samples. The results of this test are displayed in figure 7. It can clearly be seen that the equalised headphones were closer to AC quality playback than the unequalised headphones.

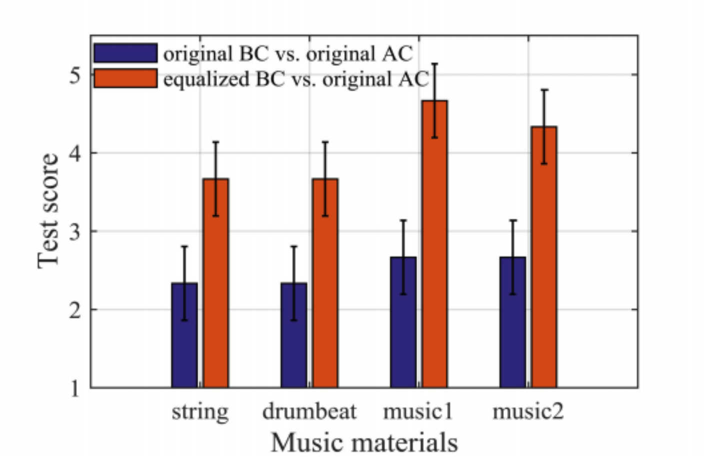

Figure 7: Results of a listening test comparing samples played unequalised BC headphones to samples played over AC headphones and the results of a listening test which compared samples played equalised BC headphones to samples played over AC headphones. Adopted from [31]

While the results of [31] are promising, previous authors have stated that they did not find a direct link between hearing thresholds and cochlear vibrations [27, 7, 6, 21]. It is possible, therefore, that the equations put forward in [31] are missing an important variable.

4 Potential Methods for Equalisation

The author proposes that are two potential methods of equalisation in BC headphones. At the present time, the author is unable to test these hypotheses as the necessary equipment is unavailable. The methods are therefore put forward here, in the hope that they are explored when possible by a researcher interested in this subject.

One potential method of equalisation requires the use of AC headphones with a known equalisation curve in conjunction with BC headphones. The proposed test procedure is:

1. The subject using the BC headphones would be asked to put on both pairs of headphones. The positioning is adjusted such that interaction between the headphones is limited as much as possible.
2. Samples of narrowband white noise in either ERB or octave bands are played over both headphones in succession.

3. The subjects are then presented with an AB comparison and asked to alter the sound level of the sample played over the BC headphone in a manner that matches it to the sample played over the AC headphones.

4. Steps 2 and 3 are repeated until the subject indicates the samples played over the AC and BC headphones are of an equal level.

5. Steps 2,3, and 4 are repeated for all samples, for a set number of repetitions.

6. The test is repeated with multiple subjects and the results are averaged across subjects.

7. An equalisation filter is then derived utilising the results. The filter could be either a parametric filter or a peaking filter for each band.

In this proposed method, there is the potential the closed ear canal skewing results. However, as noted earlier, the contribution of the open ear canal to BC hearing perception is very little. It is therefore hoped that this potential is insignificant.

A second potential equalisation technique is based on an investigation performed by Purcell et al. [19]. In their paper [19], the authors put forward a method of deriving the bone conduction transfer function utilising otoacoustic emission measurements taken from normal hearing humans.

The proposed method based on the work detailed in [19] is:

1. Measurements of otoacoustic emission are used to derive the bone conduction transfer function utilising the method detailed in [19].

2. This transfer function is then inverted to form a desired equalisation curve

3. An equalisation filter is then derived utilising the results. The filter could be either a parametric filter or a peaking filter for each band.

It is interesting to note that all previous methods were more concerned with equalistion of magnitude, while this second proposed method has the potential to equalise phase as well as magnitude. This is due to Purcell et al.'s proposed method of calculating the transfer function including a calculation of phase as well as magnitude.

5 Conclusions

In this paper, the mechanism of BC hearing perception was discussed. There are a number of factors which affect BC hearing perception due to the complex interaction of numerous pathways through which a sound signal is transmitted during bone conduction. The various components that comprise BC hearing perception are not all linear, and this introduces many non-linearities to the sound signal. In addition, the perception of sound in BC transmission is highly individualistic as the listener's physiology affects the sound signal. Bone density and skull geometry affect the impedances and resonances within the system. All of these factors and more result in difficulties in simulation and modelling of BC systems.

These factors also present difficulties in equalisation of BC headphones. Due to the nature of BC hearing perception, equalisation curves for BC headphones vary significantly from the curves for equalisation of AC headphones. However, the difficulty in measurement of the BC signal and the individualistic nature of BC hearing perception render the task of equalising BC headphones much more difficult. Existing equalisation methods consist of inverting manufacturer provided frequency response curves, or comparison of the BC transmitted signal with a signal transmitted over a loudspeaker. A more recent method proposed a derivation of an equalisation filter from a calculation of the bone-air differential curve.

This paper proposed two methods of equalisation. One method of equalisation compares BC sound samples with sound samples played through AC headphones. Another proposed method is based on the work of Purcell et al. [19], who proposed a method of calculating the transfer function for BC utilising otoacoustic emission measurements. This method postulates that the calculated BC transfer function can be inverted to form the equalisation curve.

It is hoped that in future these proposed methods will be tested. There are may also be other methods of equalisation yet to be developed as there are many facets of BC hearing perception that are still being explored.

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