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# COMPARISON OF TRANSFER FUNCTIONS OF OPEN EAR CANAL HEADSETS MEASURED ON A DUMMY-HEAD AND A HUMAN HEAD

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## ABSTRACT

Headsets that leave the ear canal open are used where environmental noise and acoustical information have to be maintained, while additional sound transmission is also required. Besides classical supra aural and in-ear phones having "hear through" functions, bone conduction and "tube-like" headsets inserted in the ear canal can be used. Usually, the transfer parameters of these devices are inferior to traditional headphones, providing decreased sound quality, sensitivity and speech intelligibility. Two different commercially available bone conduction headphones, an in-ear tube type earphone and supra aural models were tested using a dummy-head and a real human head for comparison. Measured transfer functions show the limited frequency range of open ear canal models that restricts the accessibility of such devices. Variability in repeated measurements is relatively large. Standardization of the measurement procedure for bone conduction headsets is needed, where the inclusion of human subjects can be considered.

**Keywords:** *bone conduction, transfer function, dummy-head, measurement, human head*

## 1. INTRODUCTION

Transfer function measurements of headphones differ from traditional methods targeting loudspeakers [1]. Although the transducer is usually based on the same electromagnetic principle to provide sound pressure variations on the eardrums, standardized procedures require modeling the operating conditions of a headphone. Artificial ear replicas, or even whole head models were designed to mimic the human outer ears. Dummy-heads and head and torso simulators (HATs) have become the state-of-the-art measurement equipment together with digital data acquisition hardware and software solutions.

Dummy-heads are expensive equipment, and manufacturers offer various models according to the task. Models with carefully designed ear canal and microphones at the eardrum position are more expensive, but allow for measurements of in-ear phones inserted into the ear canal. Some models have microphones at the entrance of the (blocked) ear canal. This simplified solution was shown to be appropriate for capturing directional information and can be used for selected measurement purposes [2].

Alternatively, human subjects can be used for measurements [3, 4]. This method has the advantage of being highly individual, e.g., if equalization is needed, or if personalized applications have to be developed. On the other hand, measurements are very circumstantial. Binaural microphones have to be placed at the ear canal, that are expensive and uncomfortable. Repeatability can be barely maintained in repeated measurement sessions. This is not a standardized method and thus, it does not allow for a correct comparison of different models.

A common feature of supra aural and in-ear headphones is that they block environmental sounds. Large damping (isolation) also allows for decreased volume during playback. On the other hand, safety issues arise during walking, biking or other outdoor activities. Furthermore, special application areas in assistive technology (virtual audio displays, electronic travel aids) may require an open ear canal of the user while listening to artificial sounds,

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i.e., speech commands, auditory icons, feedback, etc., via the headphone [5]. The visually impaired are one of the main focus groups.

The most typical solution is to apply bone conduction (BC) devices, also called "bone phones". Using the human skull as a vibration receiver, it can provide sound transmission along with or instead of airborne transmitted sound through the outer ears [6, 7]. Cost effective user friendly models are now commercially available. Nevertheless, overall sound quality is inferior to traditional headphones and music or speech transmission is limited both in frequency and amplitude. Furthermore, spatial attributes of sound sources during directional hearing can be presented more efficient by means of traditional headphones. Experiments were conducted to determine the possibilities of such devices even for localization tests [8–10]. There exist so called "tube-like" models based on the same principle as regular in-ear phones and earbuds, but instead of striving for the best isolation, they are designed to be reduced in size to leave part of the ear canal entrance open.

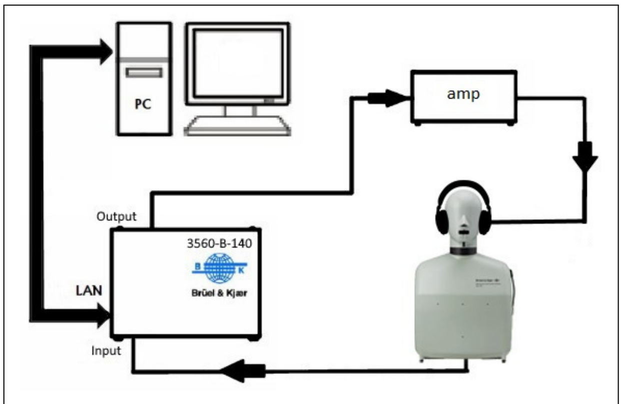


**Figure 1**. Traditional measurement setup. The dummy-head can be replaced by a human subject equipped with binaural microphones inserted into the ear canal.

Another important issue is the measurement procedure of transfer characteristics of open ear canal devices. The standardized procedure for regular headphones cannot be used, if the output signal (vibration) has to be depicted on the skull instead of the signal on the ear drum (sound pressure). Vibration on the skull and airborne coupling on the eardrum are present at the same time. Placement of the bone conduction equipment is critical for the sound quality, and inter-individual variability of different models is large. Former models used the mastoid behind the ear for signal presentation. Newer models prefer the jaw-bone before the ear. This change of excitation point has introduced additional measurement problems as well. An artificial mastoid is a standardized piece of measurement equipment, but seldom used [11–13]. Generally, commercially available BC headsets are not classified based on standardized measurements, but based on subjective evaluation (if at all).

This paper presents a traditional setup for measurements of headsets. Transfer characteristics obtained with a dummy-head and a human subject will be contrasted in the case of supra aural headphones. Measurement pitfalls will be highlighted for BC devices and a tube-like model. Conclusions will be drawn for future directions and developments.

## 2. MEASUREMENT SETUP

Fig. 1 shows the measurement setup using a dummy-head (Brüel Kjaer 4128) with a supra aural headphone. The dummy can be replaced by a human subject. The microphone outputs were connected to the data acquisition device (Brüel Kjaer Pulse) that was controlled by an external laboratory computer. The excitation signal (white noise) was generated digitally and amplified. Transfer functions were calculated as the quotient of the response and excitation automatically. For all devices, two-channel measurements were repeated ten times after replacing the headset, and averaged (arithmetic mean).

In the case of supra aural headphones, the dummy-head measurements were extended by a series of measurements on one human subject for comparison. A binaural microphone (Brüel Kjaer 4101) was inserted in the ear canal on the left and on the right side, respectively. In the case of BC devices, only airborne transmission was measured using the dummy-head. The tube-like headset could also be tested only with the dummy-head, as there was not enough space to plug the binaural microphone in the ear canal appropriately.

Fig. 2 shows the two BC devices and Fig. 3 shows the tube-like model included in the experiment.

## 3. RESULTS

### 3.1 Traditional headphones

The easiest way to compare the dummy-head and the human head method is to contrast results of the supra au-

**Figure 2**. The wired AfterShokz Sportz (top) and the AudioBone (bottom) bone conduction headsets.

ral headphones - the Sennheiser PXC450 and the Bose QC25 (Fig. 4). The red and black lines represent the transfer characteristics of two supra aural types using the dummy-head and the human head, respectively (right ear). Transfer characteristics generally show higher variations in repeated measurements around 10 kHz and above, especially inter-individually [3]. Measurements with human subjects having various shaped pinna, microphones at the ear canal entrance together with the headphone can introduce more variability and differences compared to dummy-head results. In this case, differences up to 12-18 dB can be observed around 10-15 kHz in form of anti-resonances with the human subject.

### 3.2 Open ear canal devices

The results of the bone conduction devices are shown in Fig. 5 for the left and right side, respectively (airborne only with the dummy-head). The deviations in the physical structures and in possibilities of placement on the head of BC devices can result in very different airborne frequency responses. Placing the binaural microphone in the human subject's ear canal together with the BC device on the jaw-bone showed difficulties during the measurement. Results were found to be inconclusive and inappropriate for a comparison.

**Figure 3**. The tube-like EarHero Pro model without the soft bud (left) and inserted at the entrance of the partly open ear canal (right).

The tube-like device could be positioned at the entrance of the ear canal of the dummy-head with and without a supplementary bud (Fig. 6). Due to the size of the device, a binaural microphone could not be inserted next to it; thus, only dummy-head results are available.

## 4. DISCUSSION

The main goal of the experiment was to test special headsets for applications in assistive technology, where blocking of environmental sounds is not acceptable. Introducing devices that leave the ear canal open may degrade the overall transmission quality, speech intelligibility or the accuracy of decoding of the directional information.

Furthermore, new applications in virtual and augmented reality technology require the opposite; an increased level of separation from the environment for a total immersion. As a matter of fact, the applied supra aural headphones were equipped with hear-through functions and active-noise-cancellation (ANC), and were measured with active and deactivated ANC as well. Moreover, all headsets were tested with subjects in a virtual listening test for comparison [14].

As part of the experiment, objective measurements were performed to determine the transfer characteristics of the devices using currently available equipment. The supra aural types performed well, both with a dummy-head as well as with a human subject. A difference between dummy-head and human head results can be observed in the high frequency range above 8-10 kHz as expected. Individual anatomical differences can cause large variability in the results. The standardized procedure using a dummy-head with microphones placed at the

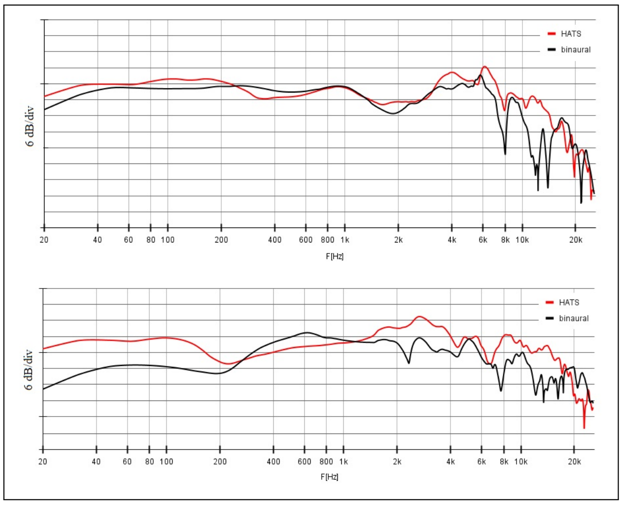


**Figure 4**. Results of two supra aural models measured on the dummy-head and on the human head (smoothed average of ten measurements of the right ear).

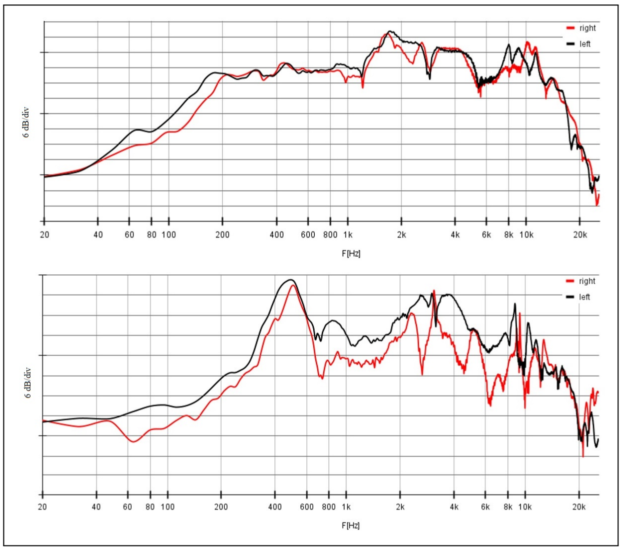


**Figure 5**. Results of the BC devices: AfterShokz (top) and AudioBone (bottom). Curves are smoothed average of ten measurements with the dummy-head.

eardrum is suggested.

In the case of BC devices, airborne transmission could be measured with acceptable precision with the dummy-head. Differences between repeated measurements and between the left and the right side were greater than with traditional headphones, because proper replacement on the head is more difficult. The placement of the transducer on the head influences the transmission quality, which was supported by subjective reports of subjects [15–17]. The pushing force between skull/skin and transducer can affect transmission quality during transmitting vibration via the bones. Inappropriate fitting may result in decreased bone conduction and increased airborne transmission. Especially in case of a human subject, small head and jaw movements can result in misplacement and the need for a constant adjustment of the device. Furthermore, one of the devices had a fixed headband that cannot be adjusted to the individual head size. The measurement procedure with binaural microphones at the entrance of the ear canal and the BC device at the jaw-bone of the human subject was found to be inappropriate for repeatable and conclusive results.

Approximating for the airborne transmission, the traditional dummy-head method can be applied, with satisfactory precision in repeated measurements. As there is no standardized method for measuring the real transmission from the input to the output on the skull, neither a dummy-head nor a real human head is capable of a correct measurement. Head and torso simulators were designed to mimic the outer shape of the human body, primarily for binaural recordings, HRTF measurements, and spatial hearing research. Great efforts were put into the design of the pinna, ear canal and coupling (impedance) by neglecting features such as material stiffness, skin or hair reproduction. It is also possible to replace an expensive binaural dummy-head with a cost-effective single-channel version or with artificial ear simulators without head geometry for simplified headphone tests.

Although an artificial mastoid is available for bone conduction tests, they are sparsely used and insufficient for devices placed on the jaw-bone. The development and standardization of bone conduction testing equipment should be directed to artificial ”skull simulators” with various excitation points for vibration detection. Furthermore, human subjects may be involved in standardized procedures in case of bone conduction. Finally, a complete method is desired where both bone conduction and airborne conduction can be determined and combined. Although there is a possibility to reduce airborne coupling by plugging the ear canal, the main feature of these devices is to allow playback by leaving it open.

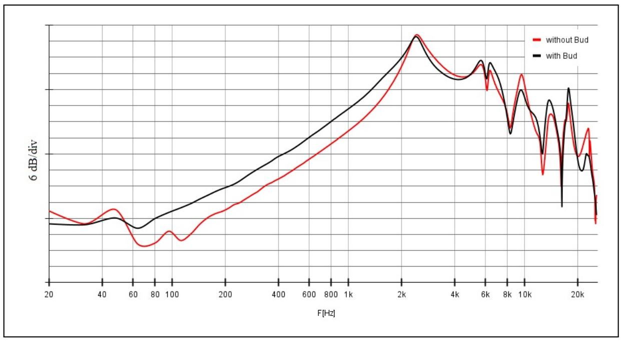


**Figure 6**. Result of the EarHero model with and without the supplemented bud (smoothed average of ten measurements of the right ear).

## 5. CONCLUSION

Current measurement setups and methods are designed for transfer function measurements of traditional headphones. Supra aural types can be tested both with dummy-heads and human subjects with binaural microphones. Results differ generally above 8-10 kHz, and the standardized dummy-head method is preferred. In-ear phones plugged into the ear canal and tube-like devices cannot be measured on human subjects, only with dummies having microphones at the eardrum position. In the case of open ear canal bone conduction devices, new methods and equipment have to be developed for correct transfer function measurements. Output signals have to be depicted on the eardrum for airborne coupling, and vibrations on different areas of the skull. Former BC devices used the mastoid position, and artificial mastoids may be available for measurements. The latest developments use the jaw-bone of the human head. Along with the developments of artificial measurement devices, human subjects may be included as well for standardized measurements of BC devices.

## 6. ACKNOWLEDGMENTS

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