Applied Acoustics 126 (2017) 19–25

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Frequency characteristics of bone conduction actuators – Measurements of loudness and acceleration

Xiuyuan Qin *, Tsuyoshi Usagawa

Department of Computer Science and Electronic Engineering, Graduate School of Science and Technology, Kumamoto University, 2-39-1 Kurokami, Chuo-ku, Kumamoto 860-8555, Japan

ARTICLE INFO

Article history:
Received 8 November 2016
Received in revised form 2 May 2017
Accepted 4 May 2017
Available online 12 May 2017

Keywords:
Bone conduction
Frequency characteristics
Acceleration
Loudness
Otoacoustic emission

ABSTRACT

Loudness as a subjective measurement and acceleration as an objective measurement were taken to measure the frequency characteristics of four different bone conduction actuators. The loudness of bone conduction was measured by balancing bone-conducted stimuli at 17 frequencies from 0.2 kHz to 8 kHz. The acceleration at equal loudness, which was measured by a Brüel & Kjær 4930 artificial mastoid, was transferred to relative levels for comparison with the loudness measurements. A relationship between loudness and acceleration was difficult to find for a bone conduction actuator of inner-ear type while for a head-of-mandible type, a relationship was found at some frequencies. Furthermore, otoacoustic emission of a head-of-mandible actuator was measured. It was hypothesized that loudness can be estimated by objective measurements of bone conduction actuators at specific frequencies.

1. Introduction

In the transmission of sound signals to the cochlea, air conduction (AC) is the main pathway for ordinary hearing. Sound signals are transmitted via the ear canal, ear drum and middle ear to the cochlea. Another means of transmission is bone conduction (BC) via the vibrations induced by bone conduction actuators on the skull. Several types of bone conduction actuator have been practically used. For example, the bone-anchored hearing aid (BAHA) [1] has been used and studied as an implanted bone conduction actuator for many years. Nevertheless, a non-invasive product is more desirable, so bone conduction actuators that can be inserted into the ear canal (BC actuator of inner-canal type) and those that can be attached on the ears have been produced and are being applied for radio communication systems and entertainment. Since no implantation is required, they are more acceptable for individuals with normal hearing ability. A bone conduction actuator of inner-canal type must to be inserted into the ear canal when used, thus its transmission may be affected by both the AC and BC pathways. Bone conduction actuators not requiring insertion are more widely used because users can keep their ear canals open to simultaneously receive sound from AC. Nevertheless, although products based on BC can be commercially utilized for music reproduction and hearing aids, the difficulty of measuring BC transmission results in unclear detailed characteristics of bone conduction actuators.

Various linear and nonlinear mechanisms, such as the movement of the ossicles in the middle ear and attenuation in the stimulation of the cochlea, are involved in the transmission through skull to cochlea [2]. Since the BC hearing perception is influenced by several factors [3], how BC is transmitted in the hearing process is still under discussion. Several researchers are studying the characteristics of the BC pathway by using cadavers or specimens with implanted bone conduction actuators [4,5], but the transmission from the skin to the inner ear by BC is still difficult to explain. The relationship between BC transmission and the vibration of cochlea was also investigated by several studies [6–8] and it was concluded that the measurement of cochlear vibration can be used to estimate BC perception, although a direct relationship between the hearing threshold and cochlear vibration was not found.

The placement of a bone conduction actuator is considered to be another factor that affects perception. In previous research, four positions have been mainly used: forehead, head of mandible, mastoid and vertex. In 1962, Studebaker [9] observed the difference performances of three different positions of bone conduction. It was found that the mastoid produced the lowest thresholds while the forehead produced the highest mean thresholds. A similar conclusion was obtained by Frank [10] who used a circular tipped vibrator to perform a comparison. Nevertheless, some research showed that when compared with the mastoid, forehead, vertex and other positions which commonly measured for electroen-

* Corresponding author.
E-mail address: xiuyuanqin@gmail.com (X. Qin).

http://dx.doi.org/10.1016/j.apacoust.2017.05.007
0003-682X/

cephalograph, head of mandible is the most receptive location since it generates the lowest overall threshold levels [11]. Additionally, some studies on the speech intelligibility of bone conduction transducer showed no significant differences in performance between mastoid and head of mandible [12]. ISO 389-3 provides a reference equivalent threshold force level (REFEL) which is defined as the output force level (OFL) set up by a bone vibrator on a specified mechanical coupler when the bone vibrator is actuated by a voltage, which corresponds to the threshold of hearing when the bone vibrator is applied to the mastoid bone [13]. The comparisons between forehead and mastoid are also given. Several studies on the mastoid have been carried out and standards have been formulated, but data for the head of mandible are unclear despite the commercial availability of bone conduction actuators.

The characteristics of bone conduction in comparison with those of AC were estimated in several previous studies. The difference between AC and BC has been discussed in [14] and investigated by using auditory brainstem responses (ABRs) [15] and bone conduction evoked otoacoustic emission (OAE) [16]. The level difference between AC and BC at different frequencies and stimulus levels may be caused by the nonlinear distortion from the bone conduction pathway which affects the spread of the sound energy [17]. Bone-conducted transmission due to BC-AC sound field excitation measured by thresholds, ear canal sound pressure and skull vibrations were compared in [18], and in this research the possibility of using BC-AC sound field sensitivity to design BC microphones was discussed.

Since there is no direct way to investigate BC transmission, an indirect method by estimating bone conduction transfer functions using OAE has been proposed [19]. OAE are the energy emissions from the inner ear back to the ear canal when stimuli are transmitted to cochlea [20]. The emissions can be measured on humans with normal hearing ability. In previous research the feasibility of using the OAE to estimate the BC transfer function objectively was discussed, and the possibility that using bone-conducted otoacoustic emission (BC-OAE) to screen hearing ability was shown in [21].

There are many research that had investigated BC transmission and tried various methods to measure frequency characteristics of bone conduction. Nevertheless, some detailed characteristics are still under discussion, resulting from the difficulty of measurements. In this research, relationship between loudness and acceleration were discussed for estimating frequency characteristics of specific bone conduction actuators. To measure BC loudness, loudness balancing between AC and BC was made by forcing subjects to compare the loudness of AC and BC. The relationship between loudness and acceleration which was given as a relative level is presented through measurements of four different bone conduction actuators: an inner-canal type and three head-of-mandible types.

2. Materials and methods

2.1. Subjects

Three subjects with normal hearing (two males and one female) with an average age of 24 years participated in the loudness measurement. Their hearing thresholds are better than 20 dB hearing level (HL) for AC stimulation and their interaural difference was less than 10 dB in the frequency range of 125 Hz to 8 kHz.

2.2. Measurement setup

All measurements were performed in an anechoic room. For loudness measurement, loudness was balanced between AC and BC to obtain the loudness for BC. AC and BC were given unilaterally to stimulate the cochlea. As stimuli, pure tones that were sampled at 44.1 kHz, and had 16-bit resolution with 1 s duration including 8.7 ms onset and offset slopes were used. In this experiment, 17 frequencies at 200 Hz to 8 kHz were measured.

Four different bone conduction actuators, an inner-canal type (BC-1), and three head-of-mandible type, BC-2 (AudioBone HGD-701), BC-3 (Trial product) and BC-4 (AudioBone MGD-03), were measured. Figs. 1–4 show the actuators that were used in the experiments. The parameters of bone conduction actuators which are used in the experiment are shown in Table 1.

Each subject was equipped with a headphone (Sennheiser HD25-1 II) and a bone conduction actuator during the experiment. A headphone amplifier (Audio-Technica AT-HA20) was connected between an audiometer and the target bone conduction actuator. Before loudness was measured, calibration was necessary to set the AC input to 60 dB SPL as a reference for BC. The settings of headphone calibration were shown in Figs. 5 and 6. A loudspeaker and a head and torso simulator (HATS) were set to calibrate the headphone used in the experiment.

Pure tones at measured frequencies were reproduced by the headphone, and the levels measured at the eardrum of the HATS were recorded by a conditional amplifier (Brüel & Kjær 2610) when the SPL was 60 dB at a position 0.1 m from the HATS as shown in Fig. 5. The recorded levels were used to calibrate the input voltages of the AC using as a reference of 60 dB as shown in Fig. 6. Considering the difficulty of measurements under a low signal-to-noise ratio (SNR), the reference voltages at 40 and 50 dB were obtained by calculations based on the values obtained at 60 dB SPL. In the acceleration measurement, an artificial mastoid (Brüel & Kjær 4930) and a conditional amplifier (Brüel & Kjær 2692) were used to measure the acceleration of the bone conduction actuators. For further discussion, otoacoustic emission was measured by Echoport ILO292 (RION).

2.3. Experiments

To obtain the BC loudness, an adaptive method was used. Stimuli generated by a personal computer were presented to subjects through an audio processor, an amplifier and a headphone or a bone conduction actuator with an earplug. A stimulus was presented either through the headphone or the targeted bone conductor. Subjects were asked to choose which side was louder, the AC input or the BC input. According to the subject's response, the level of the BC input was changed by given steps. The setup is shown in Fig. 7.

There was an interval of 1 s between AC and BC inputs. After both of inputs were presented, subjects made their choice via a

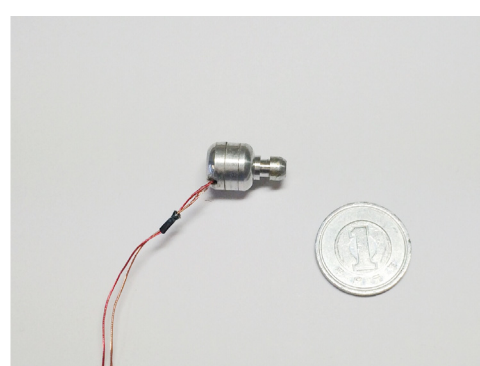

Fig. 1. Snapshot of BC-1.