On frequency characteristics of bone conduction actuators by measuring loudness, acceleration and otoacoustic emission

Xiuyuan QIN[1]; Yoshifumi CHISAKI[2]; Tsuyoshi USAGAWA[3]

[1,2,3] Kumamoto University, Japan

ABSTRACT

Bone conduction is being utilized widely for music reproduction and hearing aids. However, due to unclear transmitting process of bone conduction, some detailed characteristics are still in discussion. Previous researchers has made achievements on frequency characteristics of bone conduction actuators by comparing the relationship between loudness as a subjective measurement and acceleration as an objective measurement. In this paper, besides discussion on the possibility of estimating loudness characteristics on bone conduction actuators by means of acceleration, another method that uses otoacoustic emissions(OAEs) to estimate frequency characteristics of bone conduction is also presented. OAEs, which are acoustical signals considered to be from cochlea, are measurable of most humans with normal hearing. By giving a single stimulus to cochlea, otoacoustic emission will be transmitted into ear canal. According to the results, the emitted signal arose in response to the stimulus which was from a bone conduction actuator. It was found that similar emissions were responded to stimulus of bone conduction at the same frequency. It suggests possibility of using otoacoustic emission as a method for measuring frequency characteristics of bone conduction actuators.

Keywords: Bone conduction, Otoacoustic emission, Loudness, Acceleration, Frequency characteristic
I-INCE Classification of Subjects Number(s): 71.1.4

1. INTRODUCTION

Bone conduction which can transmit sound signal to cochlea bypassing ear canal is another way for sound transmission besides air conduction. At the present, diverse bone conduction actuators are being widely utilized as tools for music reproduction and hearing aids. Because most of bone conduction actuators does not occlude ear canals, they have large potential to apply various fields of sound reproductions and communication. Although products of bone conduction actuators are concerned in markets, some detailed characteristics are still under discussion. For instance, frequency characteristics of bone conduction actuators are still not clear. Previous research presented the measurement of bone conduction threshold depends on various conditions such as design of actuators, placement of actuators, whether the ear canals are occluded or not, as well as measurement methods (1, 2, 3, 4). Additionally, some characteristics such as threshold characteristics of some bone conduction actuators (5) and the loudness characteristics of some actuators were presented (6). To discover the frequency characteristics of various types of bone conduction actuators, i.e. inner canal type and head-of-mandible type, comparisons between loudness and acceleration of four actuators were reported (7). According to the comparison, although individual difference exists, relationship between loudness and acceleration on bone conduction actuator of head-of-mandible type can be found in specific frequency ranges, and a possibility of estimating loudness by means of acceleration in specific frequency ranges is demonstrated. Nevertheless, the relationship is still not clear due to the complexity of bone-conduction pathway.

Otoacoustic emissions are responses of the inner ear to acoustic stimulation (8). The emissions caused by stimulation is called evoked emissions. This kind of emissions such as distortion-product OAEs (DPOAEs) and transient-evoked OAEs (TEOAEs) are traditionally used in hearing screening. Additionally, ears of many normal-hearing individuals also emit spontaneously. The spontaneous otoacoustic emissions (SOAE) can be detected in many subjects without external stimuli. Less commonly measured are stimulus-frequency otoacoustic emissions (SFOAEs), arguably the simplest type of evoked emission, arising in response to a single stimulus tone (9). For air conduction, there is difficulties to measure SFOAE emission in ear canal

[1]qxiuyuan@hicc.cs.kumamoto-u.ac.jp
[2]chisaki@cs.kumamoto-u.ac.jp
[3]tuie@cs@kumamoto-u.ac.jp

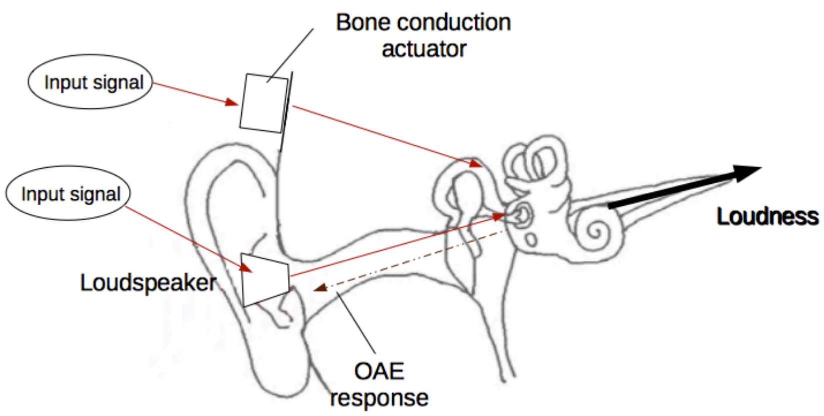

Figure 1: Pathways of air conduction, bone conduction and OAE response.

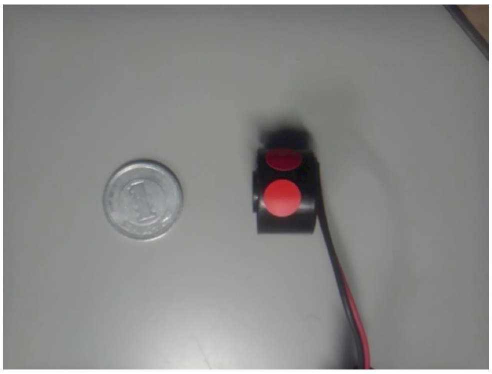

Figure 2: The bone conduction actuator used in the experiment.

Figure 3: The finished product of the bone conduction actuator used in the experiment.

since the emission and sound source are at the same frequency, but bone conduction will be less influenced by this problem. David W. Purcell, et al. (10) and Florian Kandzia, et al. (11) separately measured DPOAE of bone conduction and TEOAE of bone conduction, presenting OAEs emissions can be stimulated by bone conduction stimuli.

The assumption of air conduction, bone conduction and OAE response is shown as Fig. 1. In the pathway of bone conduction, signal is transmitted to inner ear through vibration from bone conduction actuator. Acceleration of bone conduction actuator can be measured. After signal is transmitted to inner ear, people will perceive it as sound. Additionally, inner ear will also emit OAE response to ear canal. In this paper, besides of discussion on the possibility of estimating loudness characteristics on bone conduction actuators by means of acceleration, bone conduction otoacoustic emission at particular frequencies was measured to discuss frequency characteristics of a bone conduction actuator by comparing the relationship between loudness, acceleration and otoacoustic emission.

2. EXPERIMENT METHOD

2.1 Loudness measurement

2.1.1 Materials and subjects

Figures 2 shows the bone conduction actuators used in the experiment and Fig. 3 shows a product using the bone conduction actuator made by Goldendance, Co., Ltd. The bone conduction actuator used in the experiment is head-of-mandible type and it does not occlude ear canal.

2.1.2 Calibration

Calibration is integral for measuring loudness characteristics of bone conduction actuators in this experiment. The calibration setting of the reference headphone, Sennheiser HD25-1 II, is shown as Fig. 4. Calibration and measurements were made in an anechoic chamber. As shown in Fig. 4, a loudspeaker set at 1.7m apart from the center of head and torso simulator (HATS) reproduces a pure tone. When sound level of pure tone adjusted 60 dB SPL at the position of the sound level meter, the signal level observed by internal microphone at the position of HATS's eardrum was recorded. The recorded signal level was used to adjust the input signal

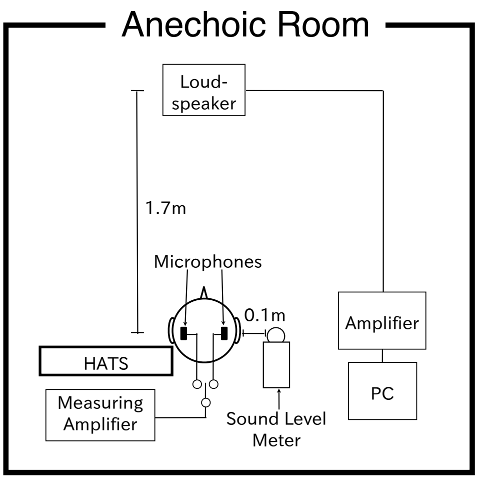

Figure 4. Schematic diagram to measure sound pressure at eardrum position of Head-And-Torso-Simulator(HATS).

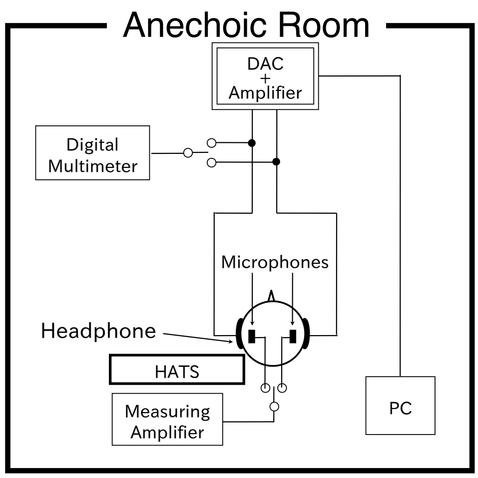

Figure 5. Schematic diagram for headphone calibration.

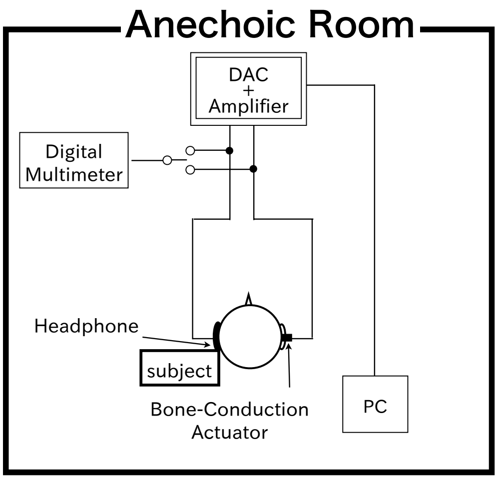

Figure 6. Schematic diagram for loudness measurement.

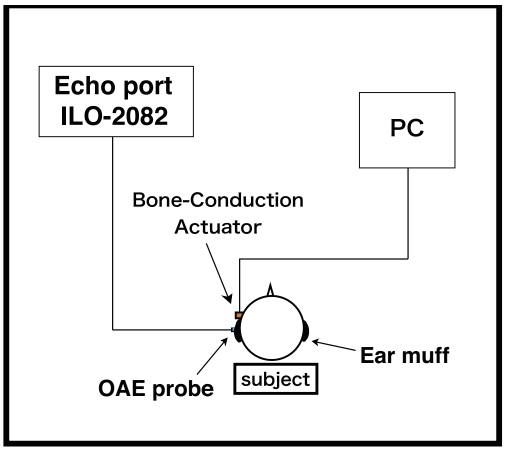

Figure 7. Schematic diagram for setting of OAE measurement.

of internal microphone of HATS to the recorded one corresponding to 60 dB SPL by the loudspeaker. The setting of this adjustment is shown as Fig 5. Calibration of the headphone's signal level is adjusted to reproduce the same signal level corresponding to 60 dB SPL, and the level was regarded as a reference. The references corresponding to 40 dB SPL were obtained by calculation according to the one for 60 dB SPL because of the low SNR when calibrating at 40 dB SPL. Calibrations were done at every frequencies which need to be measured.

2.1.3 Measurement

The reference levels were set to 40/60 dB SPL at 1 kHz. Pure tones at 44.1 kHz sampling with 16 bit resolution were used. Twenty six frequencies among 100 Hz and 12 kHz were measured. Stimuli used for the loudness balance method were pure tones with 1 s duration including 8.7 ms onset and offset slopes. In the loudness balance method, a subject heard two separate stimuli sequentially which lasted for 1 s. First stimulus was reproduced at one of the ears by the reference headphone, and second stimulus was reproduced by the bone conduction actuator on the other ear as shown in Fig. 6, and vice versa. The subjects were requested to answer whether the first stimulus was louder than the second one or not. The level of input signal of the actuator was controlled as a one-up one-down method in order to balance the loudness. Level change of the stimulus was 5 dB until the first reversal, then it was reduced to 3 dB until the third reversal, and finally set to 1 dB. The signal level corresponding to balanced loudness was obtained as the average of the last 6 times of reversals at 1 dB level. Measurement was taken on four conditions by changing the wearing ears for headphone and actuator and order of stimuli. The loudness measurement of the head-of-mandible actuator was measured with earplug to avoid influence by air conduction.

Table 1: Experimental equipments of acceleration measurements.

Apparatus	Manufacturer	Model No.
PC	Apple	MC207J/A
Digital audio processor	ONKYO	SE-U55X
Artificial mastoid	Brüel & Kjær	4930
Conditioning amplifier	Brüel & Kjær	2692
Digital multimeter	FLUKE	289

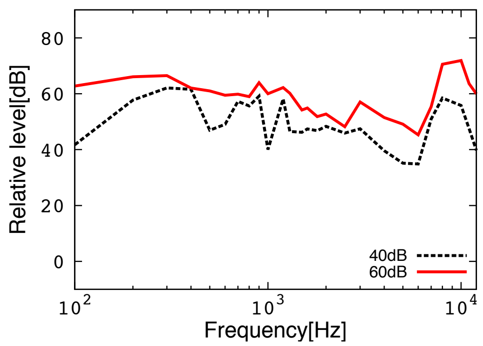

Figure 8. The result of loudness measurement of the bone conduction actuator at 40 dB and 60 dB.

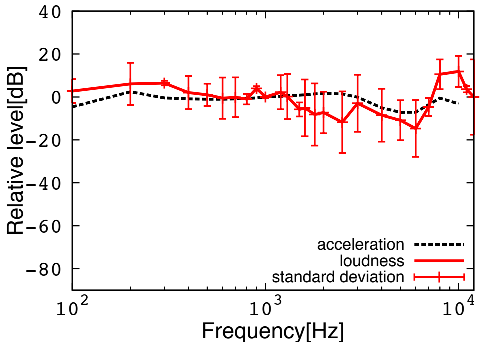

Figure 9. Comparison of acceleration measurement and psychoacoustical test measurement on the bone conduction actuator.

2.2 Acceleration

The equipment used for acceleration measurement are shown in Table 1. Acceleration characteristics of the bone conduction actuators shown in Fig.2 were measured via the artificial mastoid, B&K 4930. Stimuli were generated as 16 bit resolution at 44.1 kHz sampling. The amplitude of input signal for actuators was set on 50 mV and the output signal of the charge conditioning amplifier B&K 2692 was measured. Although the absolute acceleration was obtained in [m/s2], the characteristics were represented as the relative level against 1 kHz output signal level.

2.3 OAEs measurement

The OAEs response induced by stimulation from bone conduction actuators was measured by Echoport (RION) ILO292-USB with special OAE probe A801610Z. The setting of experiment is shown as Fig 7. Subjects wore the bone conduction actuator, and at the same time plugged OAE probe into ipsilateral ear canal. The probe was connected to Echoport(RION) ILO292-USB for transferring the OAE response data while bone conduction actuator reproduces sound signal only at the ispilateral side. The other unmeasured ear was plugged by earplugs 3M No.1100.

Subjects were requested to sit in a quiet room and keep a quiet status. The pure tones from 100 Hz to 12000 Hz were used. Sound signals at fixed sound level from bone conduction actuator were reproduced, and meanwhile the OAE responses were measured. After measured, the data of OAE response were processed by Fast Fourier Transform to obtain the signal level and frequency.

3. RESULTS

3.1 Comparison between loudness and acceleration

Figure 8 shows the results of loudness measurement of the bone conduction actuator at 40 dB and 60 dB. Although almost same sharp resonance can be found at 40 dB and 60 dB, the loudness characteristics at 40 dB show larger fluctuation than ones at 60 dB. The decline trend from 1 kHz to 6 kHz can be observed at both of this two levels. Figure 9 shows the comparison between acceleration and loudness measurements. From 400 Hz to 1300 Hz, the similar tendency can be found between acceleration and loudness, but from 1300 Hz to 2500 Hz the loudness become declining while the acceleration result is not. Although the results show complex characteristics between loudness and acceleration, it might suggest that the frequency characteristics of acceleration have a possibility to provide the estimate of the frequency characteristics of perceived loudness for the tested bone conduction actuator for the measured frequency range.

3.2 OAEs results

The results of OAE responses caused by the bone conduction actuator among three subjects are shown as Fig. 10, whereas Fig. 11 shows the comparison with loudness, acceleration and OAE response caused by

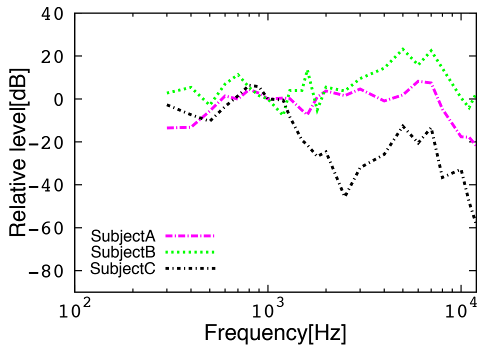

Figure 10. The OAE responses result of three subjects.

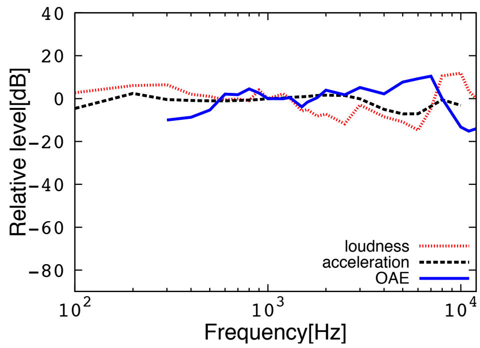

Figure 11. Comparison with loudness, acceleration and OAE response.

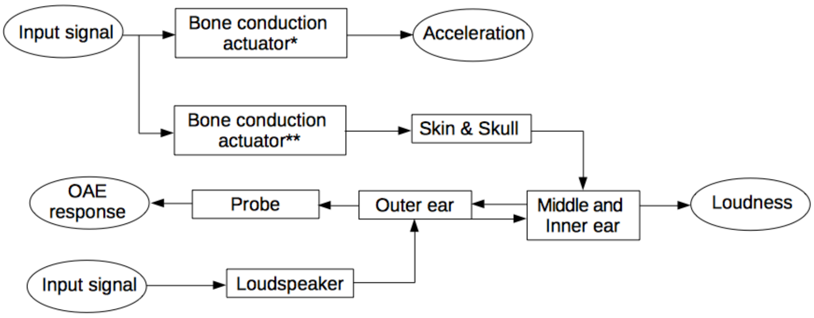

Figure 12. The assumption of relationship between loudness, acceleration and OAE response of bone conduction actuator.

the bone conduction actuator. In this experiment, no OAE responses were measured at 100 Hz and 200 Hz for subjects. Subject A and B are at the age of 24 with normal hearing ability, but subject C is a man who is 55 year old and has hearing loss. According to the result, it can be seen that the OAE response of subject C declined and much less than other two subjects in the range of 1 kHz to 12 kHz. Results of OAE response can show one's health condition of cochlea and hearing ability in some extent, so in Fig. 10 only the results of subject A and B were averaged to compare with loudness and acceleration, even though difference among subjects is obvious.

Figure 11 shows the comparison with loudness, acceleration and averaged OAE response caused by the bone conduction actuator. Ordinate is relative loudness, acceleration and OAE response referring one at 1 kHz. The OAE results were average results of subject A and B. Compared to acceleration results, from 600 Hz to 2500 Hz, OAE result shows a little fluctuation though, the differences between them are with in $\pm$ 3 dB. From 2500 Hz to 7000 Hz, OAE responses become large but acceleration declined. Comparing OAE to loudness, in the range from 900 Hz to 1600 Hz there is a similar tendency between them. From 1600 Hz to 6000 Hz, the OAE response shows ascending tendency which is different from the loudness characteristic.

* The bone conduction actuator shown in Fig. 2
** The bone conduction actuator shown in Fig. 3

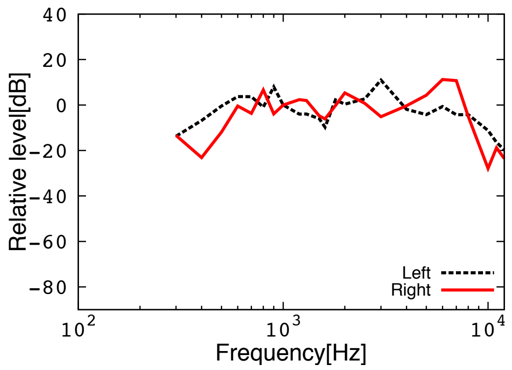

Figure 13. Result of OAE response on left and right ear of subject A.

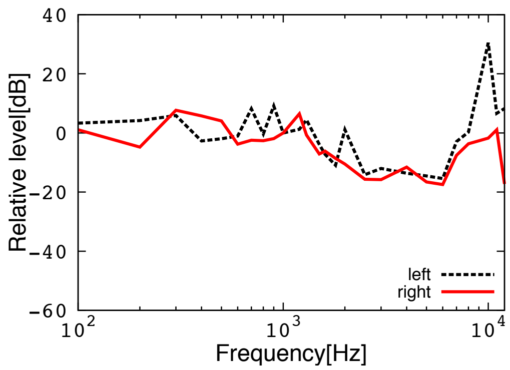

Figure 14. Result of loudness at 60 dB on left and right ear of subject A.

4. DISCUSSION

Relationship between acceleration, loudness and OAE response of bone conduction actuator is shown as Fig. 12. In air conduction, sound signal will go through ear canal, transmitted by ossicle to inner ear. In bone conduction, sound signal transmit to inner ear through skin and skull, and then will be perceived as sound by human. However, the detailed pathway of transmission is still under discussion for bone conduction. In addition, when inner ear received sound signal through air conduction or bone conduction, besides of transmitting it to auditory cortex for people's perception, OAE response will be emitted to ear canal. In this experiment, the OAE responses caused by bone conduction were measured. If the relationship between acceleration, loudness and OAE response can be cleared, it is possible to make more comprehensive discussion on frequency characteristics of bone conduction actuator.

Similar tendency can be found between loudness and acceleration of the tested bone conduction actuator at specific frequency range. As for OAE response of the tested bone conduction actuator, in the range from 600 Hz to 2500 Hz, similar tendency can be found between acceleration and OAE response. With the range of 1.5 kHz to 2.5 kHz, loudness declined while acceleration and OAE response did not have declining tendency. From 3 kHz to 6 kHz, although acceleration and loudness have similar tendency between each other, OAE response shows ascending trend. In high frequency range up to 10 kHz, OAE responses become much less, and at the same time loudness has large ascending. According to the results, similarity can be found between loudness characteristic, acceleration and OAE response in specific frequency range. There might be a possibility to estimate frequency characteristics in some extent for bone conduction actuator.

Furthermore, besides of large individual difference among subjects, difference between left and right ears also can be found. Figure 13 shows the comparison of OAE response between left and right ear of subject A. Large difference can be found between OAE response of two ears. Comparison between loudness characteristic of left and right ear was shown as Fig.14. The difference between two ears should be considered in further research.

5. CONCLUSION

In this paper, besides of discussion on the possibility of estimating loudness characteristics on bone conduction actuators by means of acceleration, another discussion about relationship between otoacoustic emissions and frequency characteristics of bone conduction is also presented. On the tested bone conduction actuator, there might be a possibility to estimate the frequency characteristics by means of loudness through ones of acceleration according to the comparison of relative frequency characteristics at specific ranges. Through the measurement of OAE response induced by the tested bone conduction actuator, some similar tendency can be found in comparison and the influence came from OAE response can be speculated. For further investigation, it is necessary to take more measurement to estimate the relationship.

6. ACKNOWLEDGEMENT

Deep gratitude to the support from Kumamoto branch of USI, the distributor of RION Co., Ltd at Kumamoto Prefecture, Japan and Goldendance. Co., Ltd.

REFERENCES

1. G.A.Studebaker. Placement of vibrator in bone-conduction testing. Journal of Speech & Hearing Research. 1962;5:321–331.

2. Bruce N.Walker, Raymond M.Stanley. Thresholds of audibility for bone-conduction headsets. Proceedings of the International Conference on Auditory Display(ICAD2005). 2005;p. 218–222.

3. R.M.Stanley and B.N.Walker. Lateralization of sounds using bone-conduction headsets. Proceedings of the Annual Meeting of the Human Factors and Ergonomics Society(HFES2006). 2006;p. 1571–1575.

4. Maranda McBride, et al. Bone Conduction Head Sensitivity Mapping: Bone Vibrator. Army Research Laboratory,ARL-TR-3556. 2005 7;.

5. Tsuyoshi Usagawa, et al. On threshold of acoustic signal provided by a bone conduction actuator. Acoustical Science and Technology(in Japanese). 2011;p. 613–616.

6. Yuki Yae, et al. On acoustic signal presentation by means of bone conduction actuator - Preliminary measurement of threshold and loudness -. IEICE Technical Report,EA2011-90(in Japanese). 2011;p. 49–54.

7. Yoshimi Fukuda, et al. On frequency characteristics of bone conduction actuators - Subjective and objective measurements of inner canal type and head-of-mandible type actuators -. Acoustics 2012 HONGKONG. 2012;.

8. Kemp, et al. Stimulated acoustic emissions from within the human auditory system. Acoustic science of America. 1978;64:1386–1391.

9. Christohper Bergevin, Analydia Fulcher, Susan Richmond, et.al. Interrelationships between spontaneous and low-level stimulus-frequency otoacoustic emissions in humans. Hearing Reseach. 2012;285:20–28.

10. David W.Purcell, Hans Kunov, William Cleghorn. Estimating bone conduction transfer functions using otoacoustic emissions. Acoustical Society of America. 2003;114:907–918.

11. Florian Kandiza and Johann Oswald, Thomas Janssen. Binaral measurement of bone conduction click evoked otoacoustic emissions in adults and infants. Acoustical Society of America. 2011;129:1464–1474.