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Improvement of sound reproducibility using open-ear-canal microphones for immersive audio applications

Koki Takahashi[1], Tsubasa Kusano[2], Zhenxiang Hong[1], Chang Sun[1], and Kan Okubo[1],

[1] *Graduate School of Systems Design, Tokyo Metropolitan University, Japan*

[2] *Huawei Technologies Japan K.K., Japan*

Correspondence should be addressed to Koki Takahashi (koki1202t@gmail.com)
and Kan Okubo (kanne@tmu.ac.jp)

ABSTRACT

The principle of out-of-head sound image localization technology is the correction of the sound stimulus at the eardrum in the free sound field and that at the eardrum of the headphone listener to equalize them. A correction filter is designed assuming that the pressure division ratio (PDR) is unity. However, it is impossible to strictly achieve a PDR of one, which can result in a timbre change of the reproduced sound. In this study, to reproduce the original sound field more faithfully, we used open-ear-canal microphones instead of the conventionally used blocked-ear-canal microphones and evaluated sound reproducibility from the viewpoint of PDR. It was found that the PDR was closer to one when recording with the ear canal open than with the ear canal blocked. In addition, the angular dependence due to the presentation direction of the sound source was reduced. The dependence on the position of the microphone placed in the ear canal was low. From the viewpoint of sound field reproducibility at the position of the eardrum, the validity of using an open-ear canal microphone was confirmed by experiments.

1 Introduction

In recent years, immersive audio has attracted considerable attention in the field of virtual reality [1]. Immersive audio technology reproduces realistic sound spaces by processing playback using headphones and loudspeakers. The implementation of immersive audio using headphones requires binaural technologies such as head-related transfer functions (HRTFs) and correction of headphone characteristics. One of the problems with binaural technology is that the timbre is not satisfactory [2,3]. Thus, it is not widely used by those who are strict about sound quality, such as sound engineers.

To localize the sound image outside the head, it is necessary to use a correction filter that equalizes the sound stimulus at the eardrum in the free sound field with that at the eardrum of the headphone listener. The correction filter for the headphones is designed such that the pressure division ratio (PDR) equals unity. The PDR is an index that expresses changes in acoustic impedance. It is derived from the sound pressure ratio measured at the ear canal and eardrum positions for free-field and headphone reproduction. When wearing headphones, the PDR deviates from one owing to the sound reflections between the microphone and headphones. Møller et al. [4–6] reported that if the headphones are ideally open, the PDR is equal to one. However, in practice, it is extremely difficult to obtain this result faithfully [7–9]. In addition, the PDR of an individual cannot be measured because measuring sound pressure at the eardrum position is difficult in a living human body. Therefore, to reproduce the original sound field, it is necessary to use microphones and headphones with PDR close to one. Otherwise, a deviation in the PDR may cause a timbre change.

In binaural recording, microphones blocking the ear canal are commonly used because of their stability [10]. In addition, blocking the ear canal is recommended when recording general HRTFs using a dummy head. This is because the recorded signal does not include the ear canal transfer function and there is little individual variation [4,6,10–13]. However, blocked-ear-canal microphones increase the acoustic impedance when wearing headphones, which changes the PDR. On the other hand, a microphone that opens the ear canal can alleviate this problem because the acoustic impedance does not change. Therefore, when making binaural recordings at the listener's head, sound field reproducibility at the eardrum position would be higher when using open-ear-canal microphones.

In this study, we evaluated the sound field reproducibility at the position of the eardrum from the viewpoint of PDR using blocked-ear-canal microphones and open-ear-canal microphones. The remainder of this paper is organized as follows. Section 2 describes the design of the correction filter and its effect on acoustic impedance. Section 3 addresses the remaining questions regarding PDR. Section 4 describes the changes in PDR and angular dependence when the ear canal is open and blocked. Section 5 describes the results of the dependence on the microphone insertion position. Finally, Section 6 presents the conclusion and summary.

2 Binaural recording and reproduction methods

This section describes the design of correction filters using the concept by Møller et al.; they placed a correction filter G for calibration between the dummy head sound pickup and playback to realize equalization of sound stimuli [4–6,11–14]. The correction filters included three methods with different recording positions [4].

2.1 Recording at the eardrum

A diagram of the method that records directly at the eardrum is shown in Figure 1. Let P_{center} be the sound pressure at the center position without a dummy head microphone, subject in the recording field, $P^{\mathrm{o,eardrum}}$ be the sound pressure at the listener's eardrum, $P_{\mathrm{hp}}^{\mathrm{o,eardrum}}$ be the sound pressure at the eardrum on the headphone playback, M be the microphone's transfer function, and E_{hp} be the headphone terminal voltage. The transfer function in the headphone playback system is as follows:

$$[P^{\mathrm{o,eardrum}} / P_{\mathrm{center}}] \cdot M \cdot G_{\mathrm{eardrum}} \cdot [P_{\mathrm{hp}}^{\mathrm{o,eardrum}} / E_{\mathrm{hp}}]. \quad (1)$$

The transfer function in the free-field system is

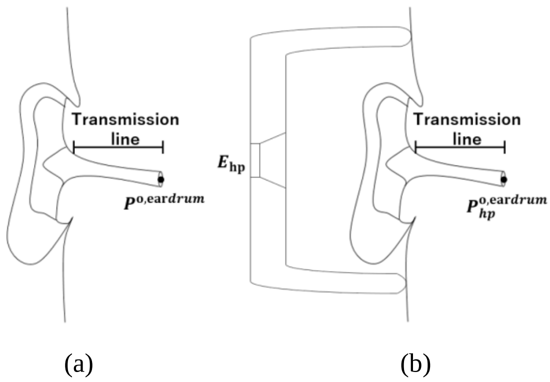


Figure 1. Binaural recording and reproduction methods at the eardrum:
(a) Free field and (b) Headphone playback.

$$[P^{\mathrm{o,eardrum}} / P_{\mathrm{center}}]. \quad (2)$$

Ideal binaural reproduction is achieved by designing a correction filter that equalizes the sound stimulus at the eardrum in the two transmission systems. The correction filter G_{eardrum} that equalizes (1) with (2) is given by

$$G_{\mathrm{eardrum}} = \frac{[P^{\mathrm{o,eardrum}} / P_{\mathrm{center}}]}{[P^{\mathrm{o,eardrum}} / P_{\mathrm{center}}] \cdot M \cdot [P_{\mathrm{hp}}^{\mathrm{o,eardrum}} / E_{\mathrm{hp}}]} = \frac{1}{M \cdot [P_{\mathrm{hp}}^{\mathrm{o,eardrum}} / E_{\mathrm{hp}}]}. \quad (3)$$

This method allows for direct recording of sound stimuli at the eardrum. However, placing a microphone immediately in front of the eardrum can be dangerous.

2.2 Recording at the entrance to the blocked ear canal

A diagram of the method that records at the entrance to the blocked ear canal is shown in Figure 2. Let $P^{\mathrm{b,earcanal}}$ be the sound pressure at the entrance of the blocked ear canal, and $P_{\mathrm{hp}}^{\mathrm{b,earcanal}}$ be the sound pressure at the entrance of the blocked ear canal on headphone playback. The transfer function in the headphone playback system is as follows:

$$[P^{\mathrm{b,earcanal}} / P_{\mathrm{center}}] \cdot M \cdot G_{\mathrm{block}} \cdot [P_{\mathrm{hp}}^{\mathrm{o,eardrum}} / E_{\mathrm{hp}}]. \quad (4)$$

As well as the derivation of Equation (3), equating equations (4) and (2), the correction filter G_{block} is derived as

$$G_{\mathrm{block}} = \frac{[P^{\mathrm{o,eardrum}} / P_{\mathrm{center}}]}{[P^{\mathrm{b,earcanal}} / P_{\mathrm{center}}] \cdot M \cdot [P_{\mathrm{hp}}^{\mathrm{o,eardrum}} / E_{\mathrm{hp}}]}. \quad (5)$$

Let $P^{\mathrm{o,earcanal}}$ be the sound pressure at the entrance of the listener's ear canal, and $P_{\mathrm{hp}}^{\mathrm{o,earcanal}}$ be the sound pressure at the entrance of the ear canal during headphone playback. G_{block} can be transformed as

$$G_{\text{block}} = PDR_{\text{open}} \cdot PDR_{\text{block}} \cdot \frac{1}{M \cdot [P_{\text{hp}}^{\text{b,earcanal}} / E_{\text{hp}}]}. \quad (6)$$

where

$$PDR_{\text{open}} = \frac{[P^{\text{o,eardrum}} / P^{\text{o,earcanal}}]}{[P_{\text{hp}}^{\text{o,eardrum}} / P_{\text{hp}}^{\text{o,earcanal}}]}, \quad (7)$$

$$PDR_{\text{block}} = \frac{[P^{\text{o,earcanal}} / P^{\text{b,earcanal}}]}{[P_{\text{hp}}^{\text{o,earcanal}} / P_{\text{hp}}^{\text{b,earcanal}}]}. \quad (8)$$

PDR_{open} is the ratio of the ear canal transfer function during free sound field and headphone playback. PDR_{block} is used to correct for the effect of the acoustic impedance and is called the PDR. Assuming that the headphone covering the ear has little effect, the transmission path from $P^{\text{o,earcanal}}$ to $P^{\text{o,eardrum}}$ is equivalent to the path from $P_{\text{hp}}^{\text{o,earcanal}}$ to $P_{\text{hp}}^{\text{o,eardrum}}$, i.e.,

$$[P^{\text{o,eardrum}} / P^{\text{o,earcanal}}] \approx [P_{\text{hp}}^{\text{o,eardrum}} / P_{\text{hp}}^{\text{o,earcanal}}]. \quad (9)$$

From Equations (7) and (9), we get

$$PDR_{\text{open}} \approx 1. \quad (10)$$

Here, three types of acoustic impedance are defined as shown in Figure 3. Z_{earcanal} is the acoustic impedance at the entrance of the dummy head's ear canal, $Z_{\text{radiation}}$ is the radiation impedance looking at the sound source side from the entrance of the ear canal, and Z_{hp} is the acoustic impedance looking into the headphone from the entrance of the ear canal. Then $[P^{\text{o,earcanal}} / P^{\text{b,earcanal}}]$ and $[P_{\text{hp}}^{\text{o,earcanal}} / P_{\text{hp}}^{\text{b,earcanal}}]$ can be expressed as

$$[P^{\text{o,earcanal}} / P^{\text{b,earcanal}}] = \frac{Z_{\text{earcanal}}}{Z_{\text{earcanal}} + Z_{\text{radiation}}}, \quad (11)$$

$$[P_{\text{hp}}^{\text{o,earcanal}} / P_{\text{hp}}^{\text{b,earcanal}}] = \frac{Z_{\text{earcanal}}}{Z_{\text{earcanal}} + Z_{\text{hp}}}, \quad (12)$$

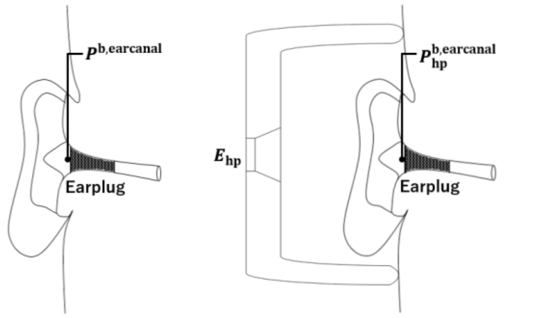
respectively. Taking the ratio of both sides of Equations (11) and (12), Equation (8) can be rewritten as

$$PDR_{\text{block}} = \frac{Z_{\text{earcanal}} + Z_{\text{hp}}}{Z_{\text{earcanal}} + Z_{\text{radiation}}}. \quad (13)$$

To approximate Equation (13) as one, Z_{hp} should satisfy

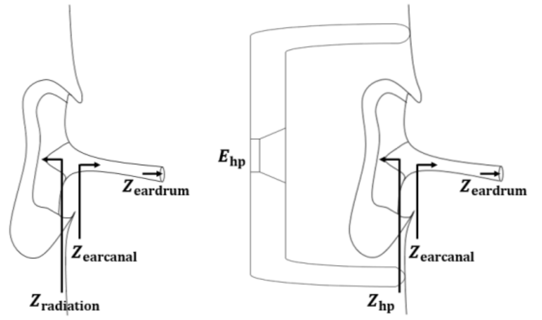
$$Z_{\text{hp}} \approx Z_{\text{radiation}}. \quad (14)$$

Headphones that satisfy Equation (14) are called open headphones or free-air equivalent coupling (FEC) (to



(a) (b)

Figure 2. Binaural recording and reproduction methods at entrance to the blocked ear canal: (a) Free field and (b) Headphone playback.



(a) (b)

Figure 3. Acoustic impedance parameters in binaural recording and reproduction methods: (a) Free field and (b) Headphone playback.

the ear) headphones. Using FEC headphones, Equation (13) becomes

$$PDR_{\text{block}} \approx 1. \quad (15)$$

Thus, when using FEC headphones, applying Equations (10) and (15) to Equation (6) yields

$$G_{\text{block}} \approx \frac{1}{M \cdot [P_{\text{hp}}^{\text{b,earcanal}} / E_{\text{hp}}]}. \quad (16)$$

This method is recommended for creating HRTFs using dummy heads. As this method blocks the ear canal, measured HRTF does not include the ear canal transfer function and is less individual. However, the FEC headphones must be used such that Equation (14) holds. If Equation (14) is not satisfied, the sound reproducibility is reduced.

2.3 Recording at the entrance to the open ear canal

A diagram of the method that records at the entrance to the open ear canal is shown in Figure 4. The transfer function in the headphone playback system is as follows:

$$[P^{\text{o,earcanal}} / P_{\text{center}}] \cdot M \cdot G_{\text{open}} \cdot [P_{\text{hp}}^{\text{o,eardrum}} / E_{\text{hp}}] \, . \quad (17)$$

Similarly, equating Equations (2) and (17),

$$\begin{aligned} G_{\text{open}} &= \frac{[P^{\text{o,eardrum}} / P_{\text{center}}]}{[P^{\text{o,earcanal}} / P_{\text{center}}] \cdot M \cdot [P_{\text{hp}}^{\text{o,eardrum}} / E_{\text{hp}}]} \\ &= PDR_{\text{open}} \cdot \frac{1}{M \cdot [P_{\text{hp}}^{\text{o,earcanal}} / E_{\text{hp}}]} . \end{aligned} \quad (18)$$

Substituting Equation (10) for Equation (18),

$$G_{\text{open}} \approx \frac{1}{M \cdot [P_{\text{hp}}^{\text{o,earcanal}} / E_{\text{hp}}]} . \quad (19)$$

Unlike the method of recording at the eardrum, the microphone is placed at the entrance of the ear canal, which is not dangerous. Also, unlike the method of recording by occluding the ear canal, there is no need to correct for changes in acoustic impedance. However, this method is unstable, because it is difficult to fix the microphone such that it does not shift.

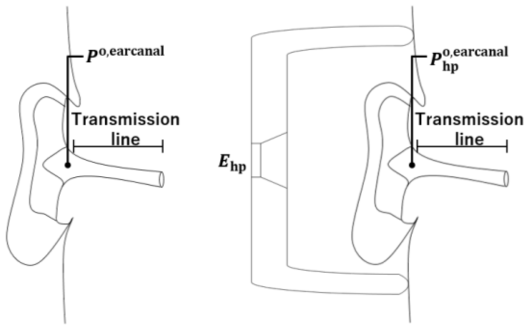
3 Is it really PDR equals one? Also, is there no angular dependence on PDR?

Ideal binaural reproduction with headphones requires the accurate correction for the sound pressure at the eardrum. To achieve that from the recordings at the entrance to the blocked/open ear canal, PDR_{open} and PDR_{block} should equal one as assumed in the previous section. For evaluating the accuracies of the correction filters G_{block} and G_{open}, we define *PDR_eardrumVSblock* and *PDR_eardrumVSopen* as follows:

$$PDR\_eardrumVSblock = PDR_{\text{open}} \cdot PDR_{\text{block}} \, , \quad (20)$$

$$PDR\_eardrumVSopen = PDR_{\text{open}} \, . \quad (21)$$

PDR_eardrumVSblock and *PDR_eardrumVSopen* represent the error of the correction filters G_{block} and G_{open}, respectively.



(a) (b)

Figure 4. Binaural recording and reproduction methods at entrance to the open ear canal: (a) Free field and (b) Headphone playback.

As aforedescribed, *PDR_eardrumVSblock* is assumed to be one when using FEC headphones. In addition, *PDR_eardrumVSopen* is assumed to be one regardless of the headphones. Furthermore, these PDRs are assumed to be independent of the direction of sound presentation. However, the question arises as to whether these statements are true. Even when using FEC headphones, acoustic impedance changes due to the blocking of the ear canal can affect these changes. This can affect the reproducibility of sound.

4 Comparison of blocked and open ear canal

4.1 Experimental conditions

In order to verify the reproducibilities of the sound when the ear canal is blocked and when the ear canal is open, we evaluated them from the viewpoint of the PDRs. The experimental environment is shown in Figure 5. The PDRs were measured using two types of headphones with dummy heads in an anechoic chamber. AKG K1000 and Sennheiser HD 650 headphones were used as FEC headphones in the measurements. The AKG K1000, an extra-aural

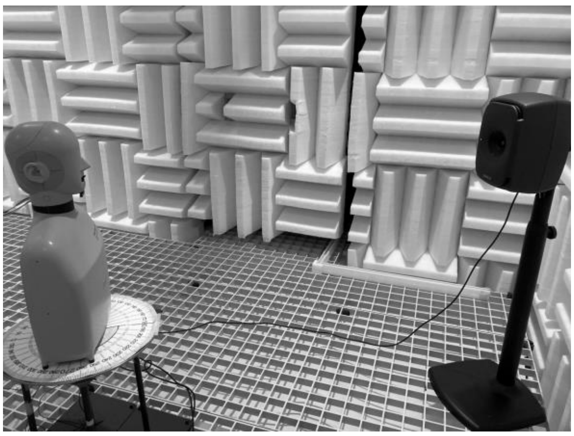


Figure 5. Experimental environment.

headphone, is completely separated from the auricle when worn. Therefore, the K1000 headphones does not need to be put on and taken off when removing the microphones; *PDR_eardrumVSblock* is close to one [6]. Sennheiser HD 650 headphones are popular in the audio industry because they can reproduce high-quality music. Since they completely cover the auricle, the HD 650 headphones require to be put on and taken off when the microphone is removed. Consequently, there is a concern that headphones may be worn at different positions during recording and playback. A B&K head and torso simulator (HATS) Type 5128 with an ear canal was used. In addition, Genelec 8341A loudspeakers were used. A DPA Core 6060 lavalier microphone with a diameter of 3 mm, as shown in Figure 6, was used as the microphone installed in the ear canal.

The blocked state of the ear canal was reproduced by blocking the ear canal using earplugs. The microphone was placed 5 mm from the entrance of the ear canal and fixed such that it did not shift when the headphones were attached or detached. By placing the HATS on a turntable and rotating it, sounds were presented from seven different directions

$(\theta = 0°, \varphi = 0°, 30°, 60°, 90°, 120°, 150°, 180°)$

on the right ear side with 0° indicating the front. Measurements were performed in triplicate and averaged. We measured four patterns using three types of microphones. In this section, we compare a single type of microphone to simplify the comparison between the open and blocked ear canals. The results measured using the other microphones are described in the Appendix.

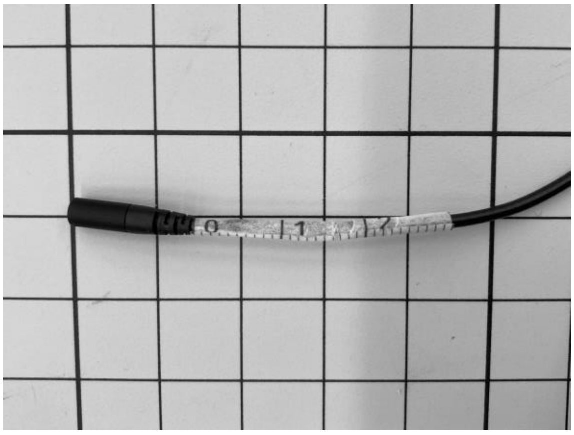


Figure 6. DPA Core 6060 microphone.

4.2 Results

Figure 7 shows the PDR results measured with open-ear-canal and blocked-ear-canal microphones using the K1000 headphones. Each color represents a different direction φ. The PDR was closer to one when recording with the ear canal open than when recording with the ear canal blocked. When the ear canal was blocked, a notch and a peak of approximately 1–3 dB were commonly generated at approximately 3–5 kHz. When the ear canal was open, *PDR_eardrumVSopen* did not exceed 1 dB up to 10 kHz. Møller reported that *PDR_eardrumVSblock* was reliable down to approximately 7 kHz [6], the PDR in our experiment was closer to one than that Møller reported.

Figure 8 shows the PDR results measured with open-ear-canal and blocked-ear-canal microphones using the HD 650 headphones. Figure 8 also indicates that the PDR was closer to one when measured in the open state than in the blocked state. A notch and peak of approximately 4–5 dB occurred at 4–6 kHz when the ear canal was blocked. This was a large value compared with the notches and peaks that occurred with the K1000 headphones, and the error was noticeable to the ear. These results suggest that sound reproduction is low with blocked-ear-canal microphones even with FEC headphones.

Figure 9 shows the ratios of the PDRs between 0° and the other six directions using the K1000 headphones. No angular dependence was observed up to approximately 7 kHz. After 7 kHz, the PDR fluctuation owing to the presentation angle was confirmed to be approximately 1–2 dB when the ear canal was open and approximately 2–3 dB when the ear canal was blocked.

Figure 10 shows the ratios of the PDRs between 0° and the other six directions using the HD 650 headphones. The same angular dependence as that of the K1000 headphone results was observed when the HD 650 headphones were used. These results indicate that the PDRs are dependent on the direction of sound presentation, and that these effects increase when the external auditory canal is blocked.

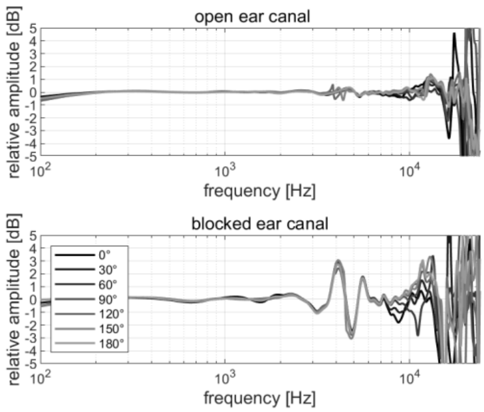


Figure 7. Amplitude of the PDRs using K1000 headphones. Each line shows measurements with sound from seven directions.

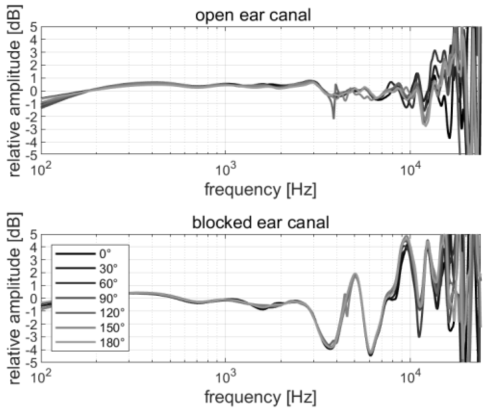


Figure 8. Amplitude of the PDRs using HD 650 headphones. Each line shows measurements with sound from seven directions.

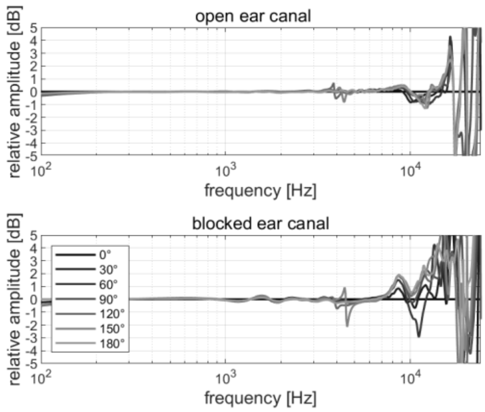


Figure 9. Amplitude ratio of the PDRs between 0° and the other six directions using K1000 headphones. Each line shows measurements with sound from seven directions.

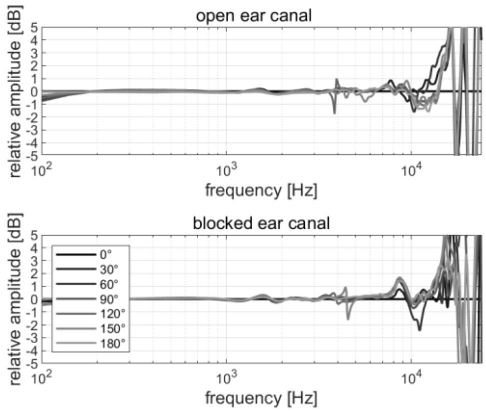


Figure 10. Amplitude ratio of the PDRs between 0° and the other six directions using HD 650 headphones. Each line shows measurements with sound from seven directions.

5 Effect of open-ear-canal microphone insertion

As described in the previous section, the PDR and its angular dependence were worse when the ear canal was blocked than when it was open. However, even when the ear canal was open, *PDR_eardrumVSopen* was not exactly one, and there was a slight degree of angular dependence. This may be attributed to an impedance change due to the insertion of the microphone, even when the ear canal is open. We investigated whether changing the depth of the open-ear-canal microphone insertion affected *PDR_eardrumVSopen*. The microphone was shifted by 5 mm from the entrance of the ear canal to the eardrum by 5 mm. The other conditions were the same as those described in Section 4.

Figure 11 shows the results for *PDR_eardrumVSopen* measured with an open ear canal and a comparison with the results at the 5-mm point using the K1000 headphones. Figure 12 shows the results obtained using the HD 650 headphones. When using the K1000 headphones, no change in *PDR_eardrumVSopen* was observed owing to the microphone insertion depth. When the HD 650 headphones were used, a change of approximately 2 dB was confirmed at approximately 6 kHz, depending on the microphone insertion position. However, this was a small change compared to the change in *PDR_eardrumVSblock* due to the blocking of the ear canal.

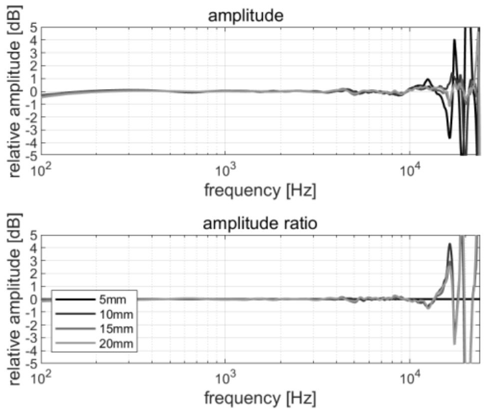


Figure 11. Amplitude of *PDR_eardrumVSopen* and amplitude ratio (based on 5mm point) of *PDR_eardrumVSopen* with open-ear-canal microphone using K1000 headphones. Each line shows measurements at different points in the ear canal.

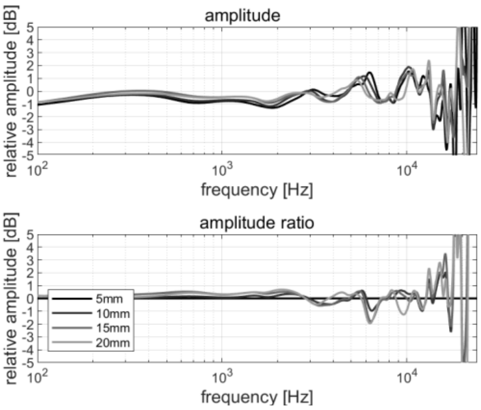


Figure 12. Amplitude of *PDR_eardrumVSopen* and amplitude ratio (based on 5mm point) of *PDR_eardrumVSopen* with open-ear-canal microphone using HD 650 headphones. Each line shows measurements at different points in the ear canal.

6 Conclusions

In this study, we conducted experiments based on the hypothesis that sound reproduction is higher when the ear canal is open than when it is blocked. Further, we evaluated them from the viewpoint of the PDRs. The results indicate that when FEC headphones were used, the PDR was closer to one when the ear canal was open than when it was blocked. This suggests that the acoustic characteristics at the position of the eardrum in binaural reproduction are approximated by the acoustic characteristics during speaker reproduction. In addition, a higher-precision binaural reproduction is expected. We also demonstrated the angular dependence of the PDRs. Furthermore, it was found that this effect increased when the ear canal was blocked. If the PDRs for each angle can be measured and estimated using some method, a more accurate binaural reproduction can be realized.

On the other hand, as regards ideal FEC headphones, such as the K1000 headphones, no change in *PDR_eardrumVSopen* was observed when changing the depth of insertion of the microphone into the ear canal. For the HD 650 headphones, the position closer to the eardrum yielded slightly better results. However, the difference due to the FEC headphones is more conspicuous and important. It is suggested that measurement of the PDR values will help in the selection of headphones when aiming for highly accurate binaural reproduction. Additionally, these findings are expected to simplify headphone correction filter design by using an open-ear-canal microphone. However, the improvement of reproducibility when using a microphone with an open ear canal poses a challenge. In the future, we intend to improve the reproducibility and estimate the PDR values.

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Appendix

Figure 13 shows the PDR measurement results obtained using two types of microphones other than the Core 6060. The microphones used were the DPA Core 4560 with a diameter of 5 mm, and a self-made microphone with a diameter of 5 mm. The microphone is small and attached to the tip of the ear. Both devices are omnidirectional microphones. The Core 4560 has a windscreen at the end of the microphone, whereas the self-made microphone uses an earplug to block the ear canal, as described in Section 3. The PDR for the two microphones was similar to the blocked-ear-canal microphone described in Section 3. This suggests that sound reproducibility is lost when the windscreen is attached, similarly to when the ear canal is blocked. Perhaps the change in acoustic impedance due to wearing a windshield is the same as when the ear canal is blocked.

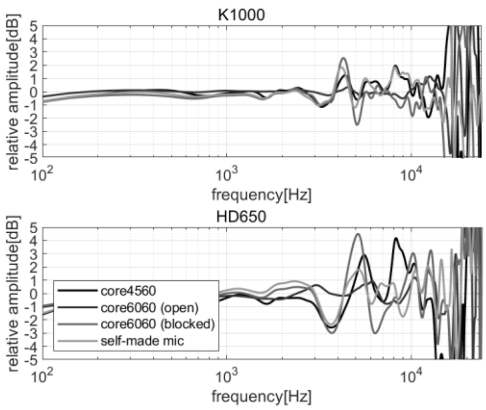

Figure 13. Amplitude of the PDRs with various microphones using K1000 and HD 650 headphones.