Applied Acoustics 155 (2019) 280–285

Contents lists available at ScienceDirect

Applied Acoustics

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

# Generation of the amplitude spectra of the individual head-related transfer functions in the upper median plane based on the anthropometry of the listener's pinnae

Kazuhiro Iida *, Hikaru Shimazaki, Masato Oota

*Spatial Hearing Laboratory, Faculty of Advanced Engineering, Chiba Institute of Technology, 2-17-1 Tsudanuma, Narashino, Chiba 275-0016, Japan*

ARTICLE INFO

*Article history:*
Received 4 January 2019
Received in revised form 17 April 2019
Accepted 5 June 2019

*Keywords:*
Head-related transfer function
Individualization
Generation
Pinna anthropometry
The median plane

ABSTRACT

In order to address individual differences in head-related transfer functions (HRTFs), individualization of HRTFs has been investigated. The amplitude spectra of individual HRTFs for seven directions in the upper median plane for 27 subjects (54 ears) were estimated from twelve pinna anthropometry and partial regression coefficients, which were obtained by multiple regression analyses. The estimated HRTFs had similar prominent notches and peaks to those for the measured early HRTFs. The spectral distortion and the correlation coefficient between the amplitude spectra of the estimated HRTFs and those of the measured early HRTFs ranged from 3.2 to 4.2 dB and 0.83 to 0.95, respectively. The inter-subject spectral difference was 7.4 $dB^2$. Then, multiple regression analyses were carried out again using 24 subjects (48 ears), who were chosen randomly from the full 27 subjects. The amplitude spectra of three naive subjects (six ears), who were not involved in the multiple regression analysis among 27 subjects, were generated using the pinna anthropometry of the subjects and the partial regression coefficients obtained from 24 subjects. The generated HRTFs had similar prominent notches and peaks to those of the measured early HRTFs, although some of the notches were shallow compared with the measured notches. The spectral distortion and the correlation coefficient ranged from 4.6 to 6.2 dB and from 0.72 to 0.91, respectively. The inter-subject spectral difference was 14.0 $dB^2$. The obtained correlation coefficients suggest the potential for generating an outline of the amplitude spectrum of the HRTFs for an unknown listener from the pinnae anthropometry, although there is a certain absolute difference that needs to be reduced between the amplitude spectrum of the generated HRTFs and the measured early HRTFs.


## 1. Introduction

Accurate three-dimensional sound image control can be accomplished by reproduction of a listener's own head-related transfer functions (HRTFs) at the entrances of the ear canals [19]. However, measurements of the HRTFs for an arbitrary listener are impractical because the measurements require a special apparatus and a great deal of time.

There exist remarkable individual differences in HRTFs. The HRTFs of other listeners often cause front-back confusion of a sound image and inside-of-head localization. This is a serious problem, which prevents acoustic virtual reality (VR) from coming into widespread practical use. Current acoustic VR, which can present three-dimensional acoustical sensation to only a specific listener, must be evolved into a universal system that can present three-dimensional acoustical sensation to everyone. In order to address this problem, methods for obtaining individualized HRTFs of an unknown listener, which do not require acoustical measurements have been investigated.

It is well known that human mechanisms for the perception of the direction of a sound fall into two categories. The cues for the perception of the lateral direction are the interaural time difference (ITD) and the interaural level difference (ILD). Methods to individualize the ITD and ILD using the dimensions of the listener's head shape have been established [9,26].

On the other hand, the cue for the perception of the vertical direction is the amplitude spectrum of the HRTF. Numerous approaches have been proposed for individualization of the amplitude spectrum of the HRTF. One such method uses principal component analysis (PCA), which resolves the amplitude spectrum of an HRTF into its principal components [12,14]. Then, the amplitude spectra of the individual HRTFs are synthesized using some of the principal components and weighting coefficients. The weighting coefficients depend on both the listener and the direction of a

* Corresponding author.
*E-mail address:* kazuhiro.iida@it-chiba.ac.jp (K. Iida).

https://doi.org/10.1016/j.apacoust.2019.06.007

sound source. Attempts were made to estimate the weighting coefficients based on the anthropometry of the listener's pinnae using multiple regression analysis [21,1] or a deep neural network [3]. However, estimation of the weighting coefficients of an unknown listener has not been successful.

Another method for HRTF individualization estimates the prominent spectral peaks and notches, which are the cues for vertical localization of the individual HRTFs. It is demonstrated that the minimum HRTF components, which provide approximately the same localization performance as the measured HRTFs were the two lowest-frequency notches and the two lowest-frequency peaks [5,7]. Furthermore, the frequency of the two notches and the two peaks were reported to be estimated from the anthropometry of the listener's pinnae [6,24,18]. However, estimation of the level of the notches and peaks has not been successful.

A number of methods have been considered in which a listener chooses the appropriate HRTFs by performing a listening test. Inter-subject differences in directional transfer functions (DTFs), which are the directional components of HRTFs, could be reduced by appropriately scaling the frequency of one set of DTFs [16]. Furthermore, it is shown that optimally frequency-scaled DTF halved the difference in quadrant error between other-ear and own-ear conditions [17]. However, one to three 20-min blocks of listening tests were required to find a listener's preferred scale factor. On the other hand, a two-step selection procedure to find the appropriate HRTFs from the non-individualized HRTFs was proposed [22]. However, the method took approximately 10 min to find the appropriate HRTFs.

Numerical calculation of HRTFs has also been studied intensively. The boundary element method (BEM) has been used to calculate HRTFs in a number of studies [11,10,13]. The results of numerical calculations by the finite-difference time-domain (FDTD) method, which is much faster than the BEM, revealed that the fundamental spectral feature of the HRTF of an individual listener can be calculated from the baffled pinna [25]. At the present, however, neither the BEM nor the FDTD method is available for ordinary listeners because special equipment, e.g., a magnetic resonance imaging system, is required to digitize the complicated shape of the pinnae of an individual listener.

The present study proposes a method by which to generate the amplitude spectra of the individual HRTFs of a naive listener in the median plane from the anthropometry of his/her pinnae and the partial regression coefficients, which were obtained by the multiple regression analyses using many subjects, as objective variables of the amplitude level of the measured early HRTFs at each discrete frequency, and as explanatory variables of the pinnae anthropometry.

## 2. Pre-processing of HRTFs

The notches and peaks in the HRTFs are generated in the pinna [23,25]. The effect of the pinnae is considered to be included in the early part of the head-related impulse response (HRIR), because the response from the pinna arrives at the entrance of the ear canal earlier than that from the torso. Iida and Oota [8] reported that the early HRIR, truncated by 96-point Blackman-Harris window includes information of the outline of the spectral notches and peaks and provides approximately the same vertical angle of a sound image as those of the usual full-length HRIR, in the upper median plane. Therefore, we used early HRTFs instead of usual HRTFs as the objective variables of the multiple regression analysis.

### 2.1. HRIR acquisition

The HRIRs of 27 Japanese adult subjects (54 ears) were measured for seven vertical angles in the upper median plane (0° to 180° in 30° steps) in an anechoic chamber. The vertical angle, which ranges from 0° to 360°, is defined as the angle measured from the front direction in the median plane, with 0° indicating the front, 90° indicating above, and 180° indicating the rear [20].

The test signal was presented in 30° steps by a loudspeaker having a diameter of 80 mm (FOSTEX FE83E) located in the upper median plane. The distance from the loudspeakers to the center of the subject's head was 1.2 m. The test signal was a swept sine wave, the duration and the sampling frequency of which were $2^{18}$ samples and 48 kHz, respectively. Earplug-type microphones [6] were used to sense the test signals at the entrances of the ear canals of the subject. The earplug-type microphones were placed into the ear canals of the subjects. The diaphragms of the microphones were located at the entrances of the ear canals. This condition is referred to as the blocked-entrances condition [23]. The HRTF was obtained as

$$HRTF_{l,r}(\omega) = G_{l,r}(\omega)/F(\omega) \quad (1)$$

where $F(\omega)$ is the Fourier transform of the impulse response, $f(t)$, measured at the point corresponding to the center of the subject's head in the anechoic chamber without a subject, and $G_{l,r}(\omega)$ is the Fourier transform of the impulse response, $g_{l,r}(t)$, measured at the entrance of the ear canal of the subject with the earplug-type microphones. Both $f(t)$ and $g(t)$ were 512 samples long. The HRIR was obtained by inverse fast Fourier transform (FFT) of the HRTF.

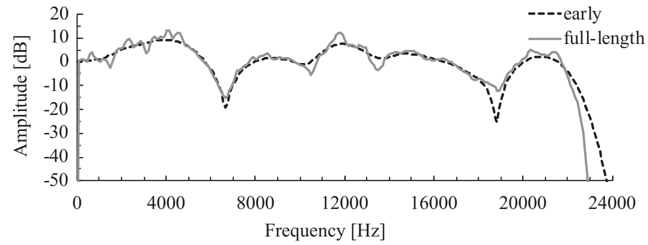


**Fig. 1.** An example of the amplitude spectra of the early HRTF (broken line) and the usual full-length HRTF (solid line).

### 2.2. Generation of early HRIRs

For each subject, ear, and vertical angle, early HRIRs were generated using the algorithm, as follows:

(1) Detect the sample for which the absolute amplitude of the HRIR is maximum, $S_{max}$.
(2) Clip the HRIR using a four-term, 96-point Blackman-Harris window, adjusting the temporal center of the window to $S_{max}$.
(3) The amplitude spectra of early HRTFs were obtained by the FFT with 512 samples.

Fig. 1 shows an example of the amplitude spectra of the early HRTF and the usual full-length (5.3 ms) HRTF. The early HRTF retains the outline of the prominent spectral notches and peaks.

## 3. Anthropometric parameters of the pinnae

Previous pinnae anthropometry parameters used in many studies [27] have the following two problems:

1) They do not express the relation between the position of the entrance of the ear canal and each region.
2) They are difficult to measure precisely.

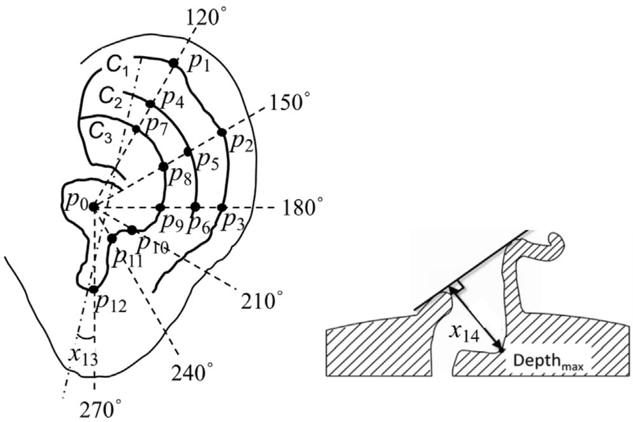


**Fig. 2.** 14 anthropometric parameters of the pinna. $x_1$ through $x_{12}$ were the lengths from $p_0$ to $p_1$ through $p_{12}$. $x_{13}$ is the tilt of the pinna, and $x_{14}$ is the depth of the concha cavity.

Therefore, we proposed 14 novel anthropometric parameters of the pinnae to be analyzed ($x_1$ through $x_{14}$), as shown in Fig. 2. The origin of the coordinate system ($p_0$) was set at the entrance of the ear canal. Then, the two-dimensional coordinates of points $p_1$ through $p_{12}$ were obtained. The points $p_1$ through $p_{12}$ are the intersections of the vertical lines (120° to 270° in 30° steps) and $C_1$ through $C_3$. $C_1$, $C_2$, and $C_3$ denote the inner border of the helix, the antihelix, the outer border of the concha, respectively [4]. Then, we defined the parameters $x_1$ through $x_{12}$ as the lengths from $p_0$ to $p_1$ through $p_{12}$. $x_{13}$ is the tilt of the pinna, and $x_{14}$ is the depth of the concha cavity. $x_{13}$ is defined as the angle between the vertical line (270°) and the line segment connecting the upper end of $C_1$ and the lower end of $C_3$.

Thirteen anthropometric pinna parameters ($x_1$ through $x_{13}$) were measured from a photograph showing an ear mold and a ruler, using image editing software (Microsoft PowerPoint). Parameter $x_{14}$ was measured directly from an ear mold using a vernier caliper.

The measured dimensions for 54 ears (27 subjects) are listed in Table 1. The individual difference (Max/Min) ranged from 1.5 to 2.6 times, except $x_{13}$ (tilt of the ear). For $x_{13}$, the value of Max/Min was 10.0.

## 4. Estimation of HRTFs by multiple regression analyses

In order to confirm the multicollinearities among pinna anthropometry, variance inflation factors (VIF) were calculated. The VIF is defined as follows:

$$\mathrm{VIF}(j) = \frac{1}{\left(1 - R(j)^2\right)} \tag{2}$$

where $R(j)^2$ denotes the determination coefficient of the multiple regression analysis using the jth explanation variable as the objective variable and other explanation variables as the explanation variables. All of the VIFs, except $x_2$ and $x_5$, were less than 10, which means that there was no multicollinearity between the explanatory variables [2].

Multiple regression analyses were carried out using 54 ears for seven vertical angles (0° to 180° in 30° steps), as objective variables of the amplitude level of the measured early HRTFs at each discrete frequency (93.75-Hz steps), and as explanatory variables of twelve pinnae parameters, except $x_2$ and $x_5$, as Eq. (3):

$$y(s, \beta, f) = \sum_{i=1}^{12} a_i(\beta, f) x_i(s) + \mathrm{b}(\beta, f) \tag{3}$$

where $y$, $s$, $\beta$, and $f$ denote the amplitude level of the measured early HRTF, the subject, the vertical angle, and the discrete frequency, respectively. $a$, b, and $x$ denote the regression coefficients, a constant, and the anthropometric parameters, respectively.

We adopted the combinations of the parameters for which the squared multiple correlation coefficient adjusted for the degrees of freedom were the highest. The obtained multiple correlation coefficients averaged over frequency (93.75 Hz to 19,968.75 Hz) for each seven vertical angles ranged 0.53 to 0.61.

### 4.1. Amplitude spectra of the estimated HRTFs

The amplitude spectra of the 54 ears were estimated using the pinna anthropometry of the subjects and the partial regression coefficients.

Fig. 3 shows examples of the amplitude spectra of the estimated HRTFs (broken line) and the measured early HRTFs (solid line). The outline of the amplitude spectra of the estimated HRTFs was similar to that of the measured early HRTFs. Most of the prominent notches and peaks in the measured early HRTFs appeared in the estimated HRTFs.

### 4.2. Spectral distortion and correlation coefficient between the estimated and measured amplitude spectra

In order to evaluate the estimation accuracy quantitatively, the spectral distortion (SD) and the correlation coefficient between the amplitude spectra of the estimated HRTFs and those of the measured early HRTFs up to 20 kHz were calculated.

The SD evaluates the mean absolute difference in amplitude spectra between the estimated HRTFs and the measured early HRTFs, as follows:

$$SD = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[20\log_{10}\left|\frac{HRTF_e(f_i)}{HRTF_{me}(f_i)}\right|\right]^2} \tag{4}$$

where $\mathrm{HRTF_e}$, $\mathrm{HRTF_{me}}$, and f denote the estimated HRTF, the measured early HRTF, and the discrete frequency, respectively.

On the other hand, the correlation coefficient is used to evaluate the similarity of the shape of the amplitude spectra between the estimated HRTFs and the measured early HRTFs, as follows:

$$r = \frac{\sum_{i=1}^{N}\left(HRTF_{me}(f_i) - \overline{HRTF_{me}}\right)\left(HRTF_e(f_i) - \overline{HRTF_e}\right)}{\sqrt{\sum_{i=1}^{N}\left(HRTF_{me}(f_i) - \overline{HRTF_{me}}\right)^2}\sqrt{\sum_{i=1}^{N}\left(HRTF_e(f_i) - \overline{HRTF_e}\right)^2}} \tag{5}$$

Table 2 shows the SD and the correlation coefficient for each vertical angle up to 20 kHz averaged over 54 ears. The SD ranged from 3.2 to 4.2 dB, and the correlation coefficient ranged from

**Table 1**
14 measured pinnae dimensions for 54 ears (mm).

| | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $x_6$ | $x_7$ | $x_8$ | $x_9$ | $x_{10}$ | $x_{11}$ | $x_{12}$ | $x_{13}$[°] | $x_{14}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ave | 35.1 | 29.0 | 22.9 | 25.3 | 21.9 | 18.2 | 15.9 | 18.5 | 15.3 | 9.5 | 9.0 | 10.9 | 22.4 | 13.8 |
| Max | 44.6 | 37.2 | 28.6 | 31.4 | 26.8 | 22.9 | 20.3 | 21.9 | 19.1 | 14.1 | 12.9 | 13.1 | 40.0 | 17.6 |
| Min | 26.4 | 21.8 | 17.6 | 18.8 | 18.4 | 14.1 | 11.0 | 14.5 | 9.7 | 5.3 | 5.3 | 7.8 | 4.0 | 9.7 |
| Max/Min | 1.7 | 1.7 | 1.6 | 1.7 | 1.5 | 1.6 | 1.8 | 1.5 | 2.0 | 2.6 | 2.4 | 1.7 | 10.0 | 1.8 |

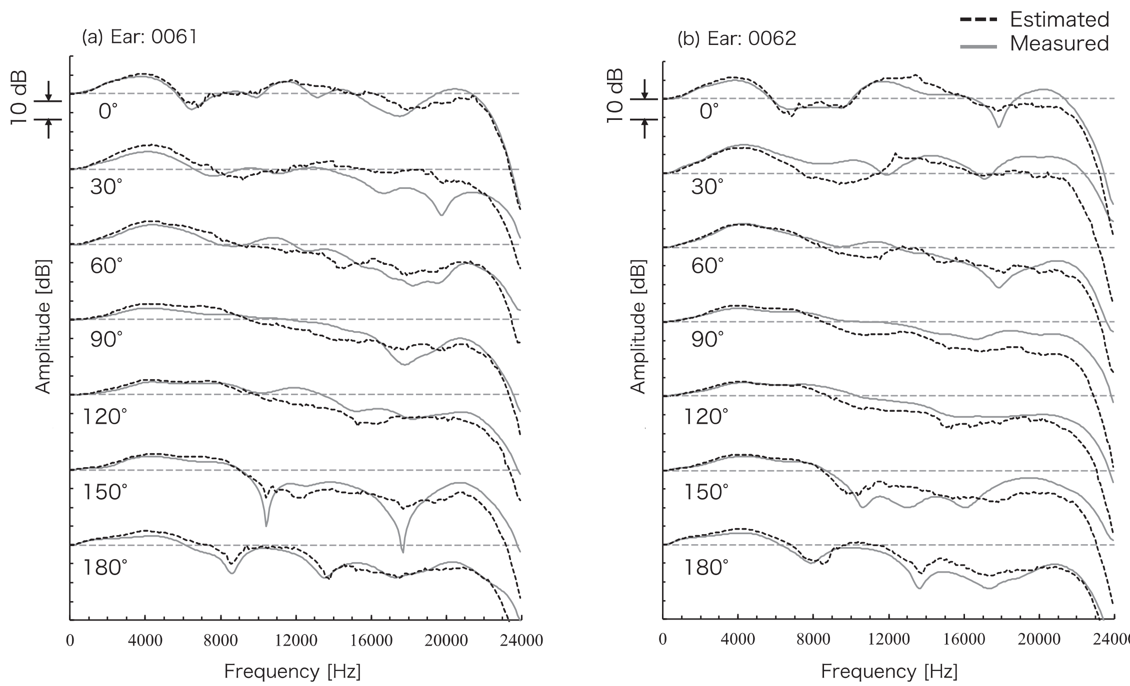


**Fig. 3.** Examples of the amplitude spectra of the estimated HRTFs (broken line) and the measured early HRTFs (solid line) in the median plane.

**Table 2**
Spectral distortion (SD) and correlation coefficient (r) between the amplitude spectra of the estimated HRTFs and those of the measured early HRTFs up to 20 kHz averaged over 54 ears.

| | 0° | 30° | 60° | 90° | 120° | 150° | 180° |
|---|---|---|---|---|---|---|---|
| *SD* (dB) | 4.2 | 3.7 | 3.6 | 3.2 | 4.0 | 3.7 | 3.8 |
| *r* | 0.83 | 0.87 | 0.93 | 0.95 | 0.94 | 0.93 | 0.89 |

0.83 to 0.95. These high correlation coefficients suggest that the outline of the amplitude spectrum of the estimated HRTFs is similar to that of the measured early HRTFs, although there is a certain absolute difference between these HRTFs.

### *4.3. Comparison of the estimation accuracy of the proposed method with that of a previous study*

Here, we compare the estimation accuracy of the proposed method with that of a previous method. Bomhardt et al. [1] resolved the amplitude spectrum of the HRTFs of 47 subjects into their principal components. Then, they estimated the amplitude spectrum using weighting coefficients based on the anthropometry of the subject's pinnae. They evaluated the estimation accuracy using not the SD, but rather the inter-subject spectral difference (ISSD), as follows [15]:

$$ISSD = \frac{1}{n_{dir}} \sum_{i=1}^{n_{dir}} \mathrm{var}\left(20\log_{10}\left|\frac{HRTF_{e,i}(f_j)}{HRTF_{m,i}(f_j)}\right|\right) \tag{6}$$

where $n_{dir}$, $\mathrm{HRTF}_{e,i}$, and $\mathrm{HRTF}_{m,i}$ denote the number of directions, the estimated HRTF, and the measured HRTF, respectively.

Note that the ISSD evaluates not the absolute difference between two HRTFs, but rather the variance (square of dB) of the ratio of the amplitude of two HRTFs. Even when using the square root of ISSD instead of the ISSD, direct comparison between the SD and the ISSD is difficult because the ISSD eliminates differences in overall gain, which are constant across frequency.

Therefore, we calculated the ISSD for the proposed method. The obtained ISSD was 7.4 dB$^2$, while Bomhardt *et al.* reported the ISSD to be 17 dB$^2$. Rigorous comparison is difficult because the target direction in the present study was considered in the upper median plane, while that in the study by Bomhardt et al. was the entire spherical surface. However, the estimation accuracy for the proposed method is assumed to be higher than that for their method.

## 5. Generation of HRTFs of the naive subjects

We examined the applicability of the proposed method to an unknown listener. Multiple regression analyses were carried out again using 24 subjects (48 ears), who were chosen randomly from 27 subjects. Then, the amplitude spectra of the three naive subjects (six ears), who were not involved in the multiple regression analysis, were generated using the pinna anthropometry of the subjects and the partial regression coefficients obtained from 24 subjects.

### *5.1. Amplitude spectra of the generated HRTFs of the naive subjects*

Fig. 4 shows examples of the amplitude spectra of the generated HRTFs and the measured early HRTFs. These two ears are identical to the ears shown in Fig. 3. The generated HRTFs had similar prominent notches and peaks to those of the measured early HRTFs. However, the similarity of the spectra of the generated HRTFs to those of the measured early HRTFs is lower than that of estimated HRTFs to those of the measured early HRTFs shown in Fig. 3. Some of the notches in the generated HRTFs tended to be shallow compared to those for the measured early HRTFs. There seems to be some room for improvement in the generation of notches.

### *5.2. Spectral distortion and correlation coefficient between the generated and measured amplitude spectra*

The spectral distortion and the correlation coefficient between the amplitude spectra of the generated HRTFs and those of the measured early HRTFs up to 20 kHz were calculated.

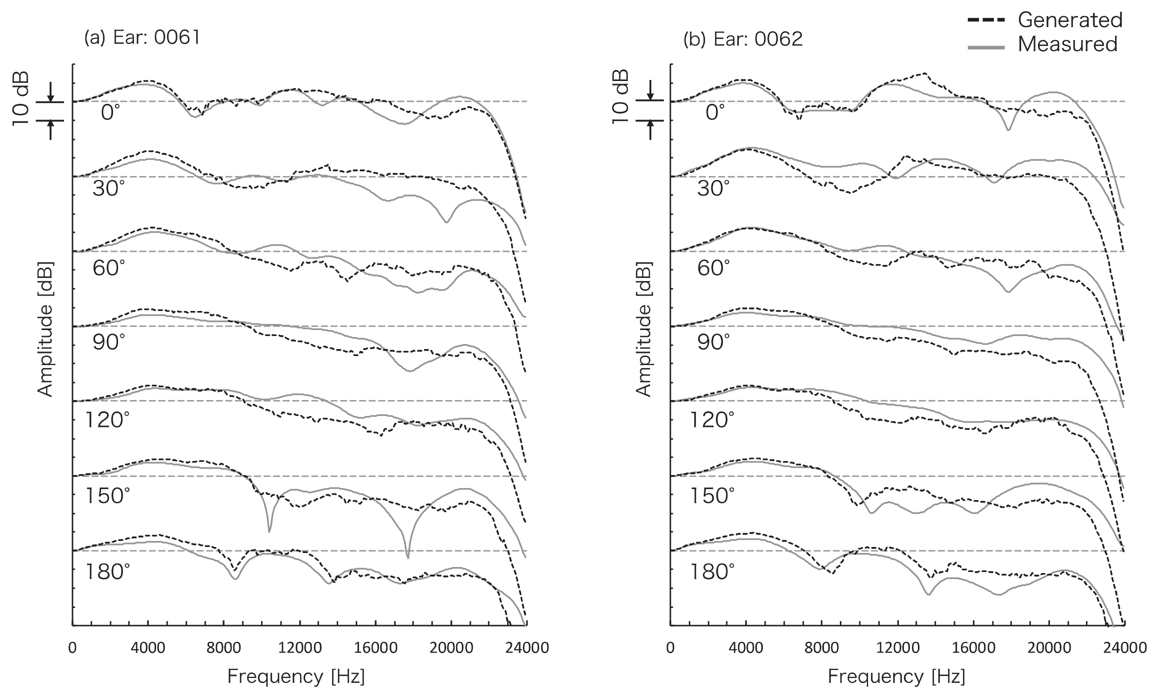


**Fig. 4.** Examples of the amplitude spectra of the generated HRTFs (broken line) and the measured early HRTFs (solid line) in the median plane for two naive ears.

**Table 3**
Spectral distortion (SD) and correlation coefficient (r) between the amplitude spectra of the generated HRTFs and those of the measured early HRTFs up to 20 kHz averaged over six naive ears.

| | 0° | 30° | 60° | 90° | 120° | 150° | 180° |
|---|---|---|---|---|---|---|---|
| *SD* (dB) | 4.6 | 4.8 | 6.2 | 5.2 | 5.4 | 4.9 | 4.7 |
| *r* | 0.75 | 0.72 | 0.86 | 0.91 | 0.89 | 0.86 | 0.84 |

Table 3 shows the SD and the correlation coefficient for each vertical angle up to 20 kHz averaged over the six naive ears. The SD ranged from 4.6 to 6.2 dB. Compared with Table 2, the SD increased for all vertical angles. The amount of increase of the SD ranged from 0.4 to 2.6 dB and tended to be relatively large for the upper directions and small for the front and rear directions. The ISSD was 14.0 dB$^2$.

The correlation coefficients ranged from 0.72 to 0.91. Compared with Table 2, the correlation coefficient decreased for all vertical angles. The amount of decrease of the correlation coefficients ranged from 0.04 to 0.15.

## 6. Conclusions

In order to address individual differences in the HRTFs of different listeners, we proposed a novel method to generate the amplitude spectra of the individual HRTFs of an unknown listener.

The amplitude spectra of the individual HRTFs of seven directions in the upper median plane for 27 subjects (54 ears) were estimated from twelve pinna anthropometry and the partial regression coefficients, which were obtained by multiple regression analyses. The outline of the amplitude spectra of the estimated HRTFs was similar to that of the measured early HRTFs. The SD and the correlation coefficient between the amplitude spectra of the estimated HRTFs and those of the measured early HRTFs ranged from 3.2 to 4.2 dB and from 0.83 to 0.95, respectively. The ISSD was 7.4 dB$^2$.

Then, multiple regression analyses were carried out again using 24 subjects (48 ears), who were chosen randomly from 27 subjects. The amplitude spectra of the three naive subjects (six ears), who were not involved in the multiple regression analysis, were generated using the pinna anthropometry of the subjects and the partial regression coefficients obtained from 24 subjects. The generated HRTFs had similar prominent notches and peaks to those of the measured early HRTFs, although some of the notches were shallow compared with the measured notches. The SD and the correlation coefficient ranged from 4.6 to 6.2 dB and from 0.72 to 0.91, respectively. The ISSD was 14.0 dB$^2$.

The obtained correlation coefficients suggest the potential for generating the outline of the amplitude spectrum of the HRTFs of an unknown listener from the pinnae anthropometry, although there is a certain absolute difference that needs to be reduced between the amplitude spectrum of the generated and measured early HRTFs.

## References

[1] Bomhardt R, Braren H, Fels J. Individualization of head-related transfer functions using principal component analysis and anthropometric dimensions. Proc. of meetings on acoustics, 2016.
[2] Chatterjee S, Hadi AS. Regression analysis by example. 5th ed. Hoboken, NJ: John Wiley and Sons; 2012.
[3] Chun CJ, Moon JM, Lee GW, Kim NK, Kim HK. Deep neural network based HRTF personalization using anthropometric measurements. Audio Eng. Soc. Convention 2017;143:9860.
[4] Geronazzo M, Spagnol S, Avanzini F. Do we need individual head-related transfer functions for vertical localization? The case study of a spectral notch distance metric. IEEE/ACM Trans Audio Speech Lang Process 2018;26:1243–56.
[5] Iida K, Itoh M, Itagaki A, Morimoto M. Median plane localization using parametric model of the head-related transfer function based on spectral cues. Appl Acoust 2007;68:835–50.
[6] Iida K, Ishii Y, Nishioka S. Personalization of head-related transfer functions in the median plane based on the anthropometry of the listener's pinnae. J Acoust Soc Am 2014;136:317–33.
[7] Iida K, Ishii Y. Effects of adding a spectral peak generated by the second pinna resonance to a parametric model of head-related transfer functions on upper median plane sound localization. Appl Acoust 2018;129:239–47.
[8] Iida K, Oota M. Median plane sound localization using early head-related impulse response. Appl Acoust 2018;139:14–23.
[9] Ishii Y, Iida K. Personalization of interaural difference cues based on the anthropometry of the listener's head – estimation of interaural time difference –. TVRSJ 2017;22:405–12 (in Japanese).

[10] Kahana Y, Nelson PA. Numerical modeling of the spatial acoustic response of the human pinna. J Sound Vib 2006;292:148–78.
[11] Katz BF. Boundary element method calculation of individual head-related transfer function. I. Rigid model calculation. J Acoust Soc Am 2001;110:2440–8.
[12] Kistler DJ, Wightman FL. A model of head-related transfer functions based on principal components analysis and minimum-phase reconstruction. J Acoust Soc Am 1992;91:1637–47.
[13] Kreuzer W, Majdak P, Chen Z. Fast multipole boundary element method to calculate head-related transfer functions for a wide frequency range. J Acoust Soc Am 2009;126:1280–90.
[14] Middlebrooks JC, Green DM. Observations on a principal components analysis of head-related transfer functions. J Acoust Soc Am 1992;92:597–9.
[15] Middlebrooks JC. Individual differences in external-ear transfer functions reduced by scaling in frequency. J Acoust Soc Am 1999;106:1480–92.
[16] Middlebrooks JC. Virtual localization improved by scaling non- individualized external-ear transfer functions in frequency. J Acoust Soc Am 1999;106:1493–510.
[17] Middlebrooks JC, Macpherson EA, Onsan ZA. Psychophysical customization of directional transfer functions for virtual sound localization. J Acoust Soc Am 2000;108:3088–91.
[18] Mokhtari P, Takemoto H, Nishimura R, Kato H. Frequency and amplitude estimation of the first peak of head–related transfer functions from individual pinna anthropometry. J Acoust Soc Am 2015;137:690–701.
[19] Morimoto M, Ando Y. On the simulation of sound localization. J Acoust Soc Jpn (E) 1980;1:167–74.
[20] Morimoto M, Aokata H. Localization cues of sound sources in the upper hemisphere. J Acoust Soc Jpn (E) 1984;5:165–73.
[21] Reddy CS, Hegde RM. A joint sparsity and linear regression based method for customization of median plane HRIR. In: 49th Asilomar conference on signals, systems and computers. p. 785–9.
[22] Seeber BU, Fastl H. Subjective selection of non-individual head-related transfer functions. In: Proc. international conference on auditory display. p. 1–4.
[23] Shaw EAG, Teranishi R. Sound pressure generated in an external-ear replica and real human ears by a nearby point source. J Acoust Soc Am 1968;4:240–9.
[24] Spagnol S, Avanzini F. Frequency estimation of the first pinna notch in head–related transfer functions with a linear anthropometric model. Proc. the 18th Int. conference on digital audio effects (DAFx-15), 2015. Trondheim, Norway.
[25] Takemoto H, Mokhtari P, Kato H, Nishimura R, Iida K. Mechanism for generating peaks and notches of head-related transfer functions in the median plane. J Acoust Soc Am 2012;132:3832–41.
[26] Watanabe K, Ozawa K, Iwaya Y, Suzuki Y, Aso K. Estimation of interaural level difference based on anthropometry and its effect on sound localization. J Acoust Soc Am 2007;122:2832–41.
[27] Zotkin DN, Hwang J, Duraiswami R, Davis LS. HRTF personalization using anthropometric measurements. Proc. IEEE Workshop on Applications of Signal Processing to Audio and Acoustics 2003.