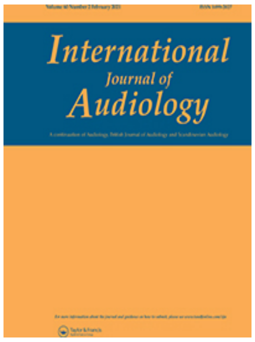

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ORIGINAL ARTICLE

Loudness functions for patients with functional hearing loss

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ABSTRACT

Objectives: To compare the loudness functions (loudness ratings as a function of sound level) obtained from patients diagnosed as having functional hearing loss (FHL) with those for patients with sensorineural hearing loss (SNHL) and healthy volunteers.

Design: Loudness functions for a 1000 Hz tone for patients with FHL and SNHL were assessed based on the categorical loudness scaling method. The data were compared with control data obtained in our facilities.

Study sample: 18 patients (33 ears) with FHL and 10 patients (19 ears) with SNHL.

Results: For patients with SNHL and healthy volunteers, loudness increased progressively with increasing sound level above the audiometric threshold, with no exceptions. However, for about 70% of the patients with FHL, a different type of loudness function was obtained; the thresholds determined from the loudness function, which were defined as the minimum sound levels at which loudness could be judged, were 10 dB or more lower than the audiometric threshold (>10 dB), and/or the loudness ratings were elevated for a sound at the audiometric threshold.

Conclusions: The results support the hypothesis that patients with FHL often make threshold judgments based on a certain loudness.

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KEYWORDS
Functional hearing loss; pseudohypacusis; loudness function; Békésy audiometry; categorical loudness scaling

1. Introduction

The loudness function, which is defined as the loudness rating as a function of sound level, is one of the most important auditory functions at the supra-threshold level (Scharf 1978; Moore 2008). The loudness function in pathological ears is known to depend on the nature of the pathology. Loudness recruitment is a well-known characteristic of sensorineural hearing loss (SNHL) due to inner ear pathology, but the degree of loudness recruitment differs among individuals with similar audiometric thresholds. Loudness recruitment is not typically observed for hearing loss due to retrocochlear pathology (Hallpike and Hood 1959; Scharf 1978; Moore 2008). Clinically, it is basically necessary to consider the sense of loudness in the fitting of hearing aids and the mapping of cochlear implants (Kollmeier 1990; Hidaka et al. 1998; Chen and Zhang 2006; Oetting et al. 2018).

To assess the loudness function, the alternate binaural loudness balance (ABLB) procedure can be applied when the hearing loss is unilateral (Fritze 1980; Terkildsen and Tingsgaard 1973; Knight and Margolis 1984). Assessment of the loudness function for patients with bilateral hearing loss is usually based on loudness ratings for tones or noise bands with a range of levels (Allen, Hall, and Jeng 1990; Suzuki et al. 1995, 1996, 1999; Trevino, Jesteadt, and Neely 2016; Busby and Au 2017; Wróblewski et al. 2017; Rader et al. 2018; van Beurden et al. 2020). In our hospital (Department of Otolaryngology-Head and Neck Surgery, Tohoku University Hospital), loudness functions have been measured as a basic auditory function tests for assessing the degree of loudness recruitment, if attending doctors wish to know it.

In addition to cases with SNHL, loudness assessment has been used for the diagnosis of functional hearing loss (FHL), which is also referred to as non-organic hearing loss or pseudohypacusis. In FHL, despite the elevation of hearing thresholds as determined by the pure tone audiogram, findings from the objective assessment of auditory functions such as otoacoustic emissions (OAEs) and auditory brain stem responses (ABRs) are basically normal. The threshold elevation observed in pure tone audiometry cannot be explained on the basis of an organic pathology (Saravanappa, Mepham, and Bowdler 2005; Drouillard et al. 2014). Psychophysically, FHL is characterised by several characteristics, specifically: a type V pattern in Békésy audiometry, in which the threshold determined using a continuous tone is lower than that determined using a pulsed signal; a discrepancy between the audiometric threshold and the speech detection level; and little or no complaint of actual hearing disturbance (Rintelmann and Harford 1967; Pracy et al. 1996). Especially, a type V pattern in Békésy audiometry is often observed for patients with FHL, but seldom for patients with SNHL or subjects with normal hearing. The type V pattern is thought to be caused by the detection threshold for patients with FHL being judged based on a certain loudness, greater than that at the "true" threshold (Rintelmann and Carhart 1964; Rintelmann and Harford 1967). However, the actual loudness functions for patients with FHL remain unclear.

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This study aimed to clarify the form of the loudness functions for patients with FHL and to compare them with those for patients with SNHL and healthy volunteers.

2. Materials and methods

2.1. Patients

This study retrospectively examined eighteen patients whose loudness functions were assessed under the diagnosis of FHL (33 ears; 1 male, 17 females; mean age ± standard deviation (SD), 18.1 ± 6.2 years; age range, 10–31 years) and 10 patients whose loudness functions were assessed under the diagnosis of SNHL due to inner ear disorders (19 ears; 1 male, 9 females; mean age ± SD, 54.8 ± 18.4 years; age range, 19–75 years) in the outpatient clinic of the Department of Otolaryngology-Head and Neck Surgery, Tohoku University Hospital, Japan from 2015 to 2019.

Clinical data for patients with FHL are shown in Table 1. ABRs in response to click stimuli, which were presented at 10 Hz, were recorded using a commercially available signal processor (Neuropack S1 MEB 9402, Nihon Kohden, Tokyo, Japan). The responses to 1000 stimuli were filtered using a 50–3000 Hz band-pass filter, and then amplified and averaged. The level of click stimuli was usually decreased in 10-dB steps from 105-dB nHL until 35 dB nHL was reached, after measuring the response to clicks presented at 105 dB nHL three times. Thus, in Table 1, the ABR threshold is expressed as "35 ↓," when wave V of the ABR could be visually detected for 35-dB clicks (detectable at 35 dB nHL). Moreover, the latencies of waves I and V as well as I-V wave intervals were assessed based on 105-dB clicks (average of three measurements). Distortion product otoacoustic emissions (DPOAEs) at 2f1-f2 were measured using a GSI 70 Automated OAE System (RS 32 marketed by RION Co., Ltd., Kokubunji, Tokyo, Japan), for $f2 = 1500$, 2000, 3000, 4000, 5000, and 6000 Hz. The frequency ratio f1/f2 was 1.2, and the levels of the primaries were 65 dB (L1) and 55 dB (L2), respectively. The level of the DPOAE was judged as normal when it was greater than the boundary of the normal value (about 0 to −2 dB SPL) indicated by the device and judged as "pass" by the device. In most cases, levels of DPOAEs were greater than 5–10 dB SPL.

Among the 18 FHL cases, case 5 had a history of damage to the left temporo-occipital lobe and left inner ear disorder due to a traffic accident at 6 years of age. The audiograms of this patient, measured regularly after the injury, showed normal hearing for 3–4 years after the temporary left inner ear disorder. After that, the audiometric threshold increased suddenly without any significant change in the DPOAE and ABR. She was then diagnosed as having FHL and has been followed up as such for about 10 years.

Case 18 was had possible mild hearing loss since childhood. Although the level of DPOAEs was lower than normal because of possible hair cell damage, a large discrepancy was observed between the ABR and audiometric thresholds. Thus, this case was also diagnosed as FHL. The present study was approved by the ethics committee of the Tohoku University Graduate School of Medicine (#2019-1-135) and performed in accordance with the guidelines of the Declaration of Helsinki.

2.2. Loudness function measurements

The loudness function for a 1000 Hz tone was assessed using the one-step subdivision categorical loudness scale shown in Figure 1, since this method is very simple, its resolution is as high as that for the two-step subdivision categorical scaling method (Suzuki et al. 1999). Participants rated the loudness of each tone on a 17-point scale (from 0 to 16) with seven labelled points (cannot hear, very soft, soft, medium, loud, very loud, and too loud). The 1000 Hz tone bursts (duration: 490 ms) were presented once per second using a commercially available audiometer with headphones (audiometer: RION AA-HA; headphones: RION AD-02T, RION Co., Ltd., Tokyo, Japan). The level of the tone was increased from an inaudible level to 90 dB HL or the too-loud level in 5-dB steps (ascending method). The monaural loudness function for each ear was measured twice (alternating between ears), and the average rating for each level was determined. The threshold determined from the loudness function was defined as the minimum sound pressure level at which the average rating of two measurements was 1 or higher.

The data were compared with control data obtained in our facilities from 12 healthy volunteers (24 ears) without any history of auditory or neurological disorders. All 12 healthy volunteers had audiometric thresholds of 20 dB HL or lower for audiometric frequencies from 125 to 8000 Hz.

2.3. Statistical analysis

In the present study, based on the loudness function, "the threshold difference between the audiometric threshold at 1000 Hz and the threshold determined from the loudness function" and "loudness ratings at the audiometric threshold for 1000 Hz" were compared between the three groups using one-way analysis of variance (ANOVA) with Bonferroni post-hoc analysis using IBM SPSS software version 26 (IBM Corp., Armonk, NY). Values of $p < 0.05$ were considered to indicate statistical significance.

3. Results

Typical loudness function examples (loudness rating as a function of sound level) obtained from patients with SNHL and healthy volunteers are shown in Figure 2(A,C), respectively. In both cases, the loudness function increased from around the threshold level determined by audiometry (audiogram threshold). For the patient with SNHL, the loudness function was steeper, showing loudness recruitment.

In Figure 2(B,D), the normalised loudness functions, in which all levels were expressed relative to the level at the audiometric threshold for the individual participant, are shown for all cases. In all cases, the loudness function increased from around the audiometric threshold.

The loudness functions for patients with FHL are shown in Figure 3. The loudness functions were roughly classified into three types: type A, for which the threshold determined by the loudness function was lower than the audiometric threshold by more than 10 dB; type B, for which the threshold determined by the loudness function was almost equal to the audiometric threshold (threshold difference ≤ 10 dB); and type C, for which the loudness rating increased abruptly when the sound level exceeded a certain value. Types A and C appear to be specific to patients with FHL. The type of loudness function for each ear of the patients with FHL is shown in the last column of Table 1.

Figure 4(A,B) compares the differences between the thresholds determined by audiometry and estimated from the loudness function and the loudness rating in response to the sound at the audiometric threshold level for patients with SNHL, patients

Table 1. Clinical data for patients with FHL.

Case	Sex	Age at exam (years old)	Elapsed time from onset (month)	Motive for consultation	Past history/Psychological background etc.	Subjective symptoms of hearing loss	Ear (R/L)	PTA (dB)	Type V in Békésy audiometry	ABR threshold of wave V: threshold of wave V (dB)	wave I latency (ms)	wave V latency (ms)	wave I-V interval (ms)	Threshold in speech audiometry (dB)	DPOAE	Loudness function type
1	F	10	40	RME (S)	NONE	NONE	R	96.25	–	35 ↓	1.27	5.1	3.83		WNR	A
							L	91.25	–	35 ↓	1.35	5.3	3.95	poor(10%)	WNR	A
2	F	17	108	RME (S)	NONE	NONE	R	47.5	N.E.	35 ↓	1.4	5.6	4.2	N.E.	WNR	A
							L	51.25	N.E.	35 ↓	1.26	5.36	4.1	N.E.	WNR	A
3	M	15	12	RME (S)	NONE	NONE	L	52.5	N.E.	35 ↓	1.25	5.12	3.87	N.E.	WNR	B
4	f	17	108	RME (S)	Stress at school	Sometimes	R	76.25	+	35 ↓	1.35	5.35	4	N.E.	WNR	C
							L	71.25	+	35 ↓	1.45	5.51	4.06	N.E.	WNR	C
5	f	20	108	HI?	Traumatic damage of left .temporal lobe (6 y.o.)	Slightly	R	58.75	–	35 ↓	1.22	5.34	4.12	50	WNR	B
							L	68.75	–	35↓	1.23	5.19	3.96	60	WNR	B
6	F	11	24	HI?	stress at school	slightly	R	41.25	+	35 ↓	1.25	5.51	4.26	N.E.	WNR	B
							L	38.75	+	35 ↓	1.22	5.49	4.27	N.E.	WNR	B
7	F	22	156	RME (S)	None	None	R	72.5	–	35 ↓	1.2	5.05	3.85	70	WNR	A
							L	75	+	35 ↓	1.2	4.98	3.78	70	WNR	A
8	F	16	60	RME (S)	None	None	R	70	–	35 ↓	1.29	5.19	3.9	40	WNR	A
							L	67.5	+	35 ↓	1.28	5.18	3.9	35	WNR	A
9	F	16	84	RME (S)	None	Slightly	R	70	+	25 ↓	1.33	5.02	3.69	20	WNR	A
							L	67.5	+	25 ↓	1.35	4.98	3.63	25	WNR	A
10	F	13	6	RME (S)	ASD	Slightly	R	95	+	35 ↓	1.25	5.18	3.93	90	WNR	A
							L	100	+	35 ↓	1.23	5.2	3.97	90	WNR	A
11	F	27	12	HI?	PTSD	Moderate	L	43.75	+	35 ↓	2.05	5.87	3.82	30	WNR	B
12	F	12	48	RME (S)	None	None	R	61.25	+	35 ↓	1.23	5.57	4.34	40	WNR	B
							L	68.75	+	35 ↓	1.27	5.42	4.15	35	WNR	B
13	F	10	6	HI?	None	None	R	58.75	–	35 ↓	1.28	5.15	3.87	5	WNR	A
							L	61.25	–	35 ↓	1.27	4.96	3.69	5	WNR	A
14	F	24	3	HI?	Atresia (contra ear)	Moderate	L	68.75	+	35 ↓	1.18	5.01	3.83	10	WNR	B
15	F	31	5	RME (O)	Epirepsy	Slightly	R	91.25	–	35 ↓	1.54	5.41	3.87	55	WNR	C
							L	72.5	+	35 ↓	1.38	5.29	3.91	75	WNR	C
16	F	19	16	HI?	Diabetes mellitus	Slightly	R	62.5	+	35 ↓	1.22	5.11	3.89	30	WNR	A
							L	63.75	+	35 ↓	1.23	5.1	3.87	40	WNR	A
17	F	18	108	RME (S)	None	None	R	56.25	+	35 ↓	1.16	5.34	4.18	50	WNR	A
							L	50	–	35 ↓	1.26	5.24	3.98	50	WNR	B
18	F	27	240	RME (S)	Mild SNHL/stress at school	Slightly	R	71.25	+	35 ↓	1.32	5.57	4.25	55	Deteriorated	A
							L	80	+	35 ↓	1.4	5.39	3.99	60	Deteriorated	A

PTA: pure tone average ((500 Hz + 1000 Hz + 2000 Hz + 4000 Hz)/4); N.E.: not examined; HI?: episodes of suspected hearing impairment; ASD: autism spectrum disorder; RME(S): routine medical examination at school; WNR: within normal range; PTSD: post-traumatic stress disorder; RME(O): routine medical examination at office.

with FHL, and healthy volunteers. Differences between groups were assessed using a one-way ANOVA with Bonferroni post-hoc analysis. The results are shown in Table 2. No significant differences were found between the patients with SNHL and healthy volunteers; however, the difference between the audiometric threshold and that estimated from the loudness function and the loudness rating scores at the audiometric threshold level was significantly larger for patients with FHL than for those with SNHL and healthy volunteers.

The participants categorised as type A could rate the loudness of sound that was judged inaudible in audiometry. The threshold difference between audiometry and the loudness measurement may have been the result of different instructions for the two measurements. To assess the effects of the instructions, audiometry and Békésy audiometry were performed under different instructions ("respond when the presented sound is perceived as being very soft") from those used for the routine measurements ("respond when any sound (even a small sound) is heard") for

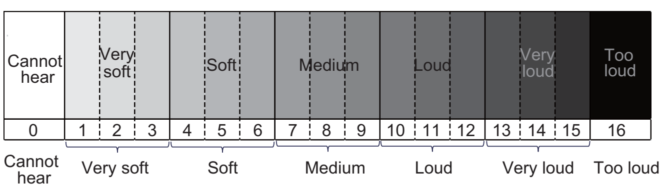

Figure 1. The one-step subdivision categorical loudness scaling scale used in this study. The participants rated the loudness of each tone on a 17-point scale (from 0 to 16) with seven labelled categories (cannot hear, very soft, soft, medium, loud, very loud and too loud).

the three cases (7, 8 and 9) categorised as type A. Representative results (case 8) are shown in Figure 5. The audiometric threshold measured with audiometry often improved markedly with the different instructions.

4. Discussion

In this study, loudness functions obtained from patients with FHL were compared with those obtained from patients with SNHL and healthy volunteers. For the latter two groups, the loudness function increased from a sound level around the audiometric threshold, with no exceptions. However, for about 70% of the patients with FHL, a loudness function unique to FHL was obtained; the thresholds determined from the loudness function were lower than the audiometric threshold by more than 10 dB, and/or the loudness ratings were elevated for a sound at the audiometric threshold.

To our knowledge, no report has been published on loudness functions for patients with FHL. However, the audiometric threshold for patients with FHL has been suggested to be based on a certain loudness, greater than that at the "real" detection threshold, based on the type V pattern in Békésy audiometry (Rintelmann and Carhart 1964; Rintelmann and Harford 1967). In Békésy audiometry, the threshold determined using a continuous tone is seldom lower than that determined using a pulsed signal for healthy patients and those with hearing loss due to an organic lesion. A type V pattern, in which the threshold determined using a continuous tone is lower than that determined using a pulsed signal, is observed only for patients with FHL. Based on the fact that a type V Békésy audiometry pattern can

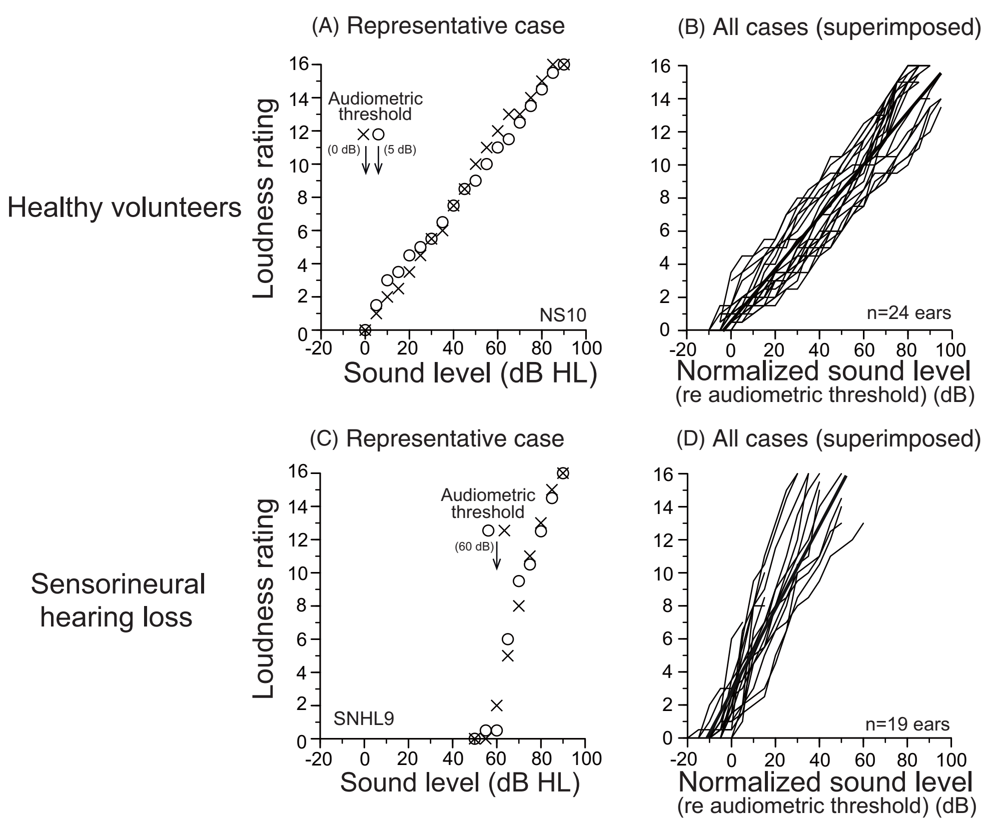

Figure 2. (A, C) Typical examples of the loudness functions (loudness rating as a function of sound level) obtained from a healthy volunteer and a patient with sensorineural hearing loss (SNHL), respectively. Data for the right and left ears are represented as circles and crosses, respectively. Arrows in the figures indicate the thresholds determined by routine audiometry. (B, D) Superimposed normalised loudness functions (normalised based on the audiometric threshold) for all the cases obtained from healthy volunteers and patients with SNHL, respectively.

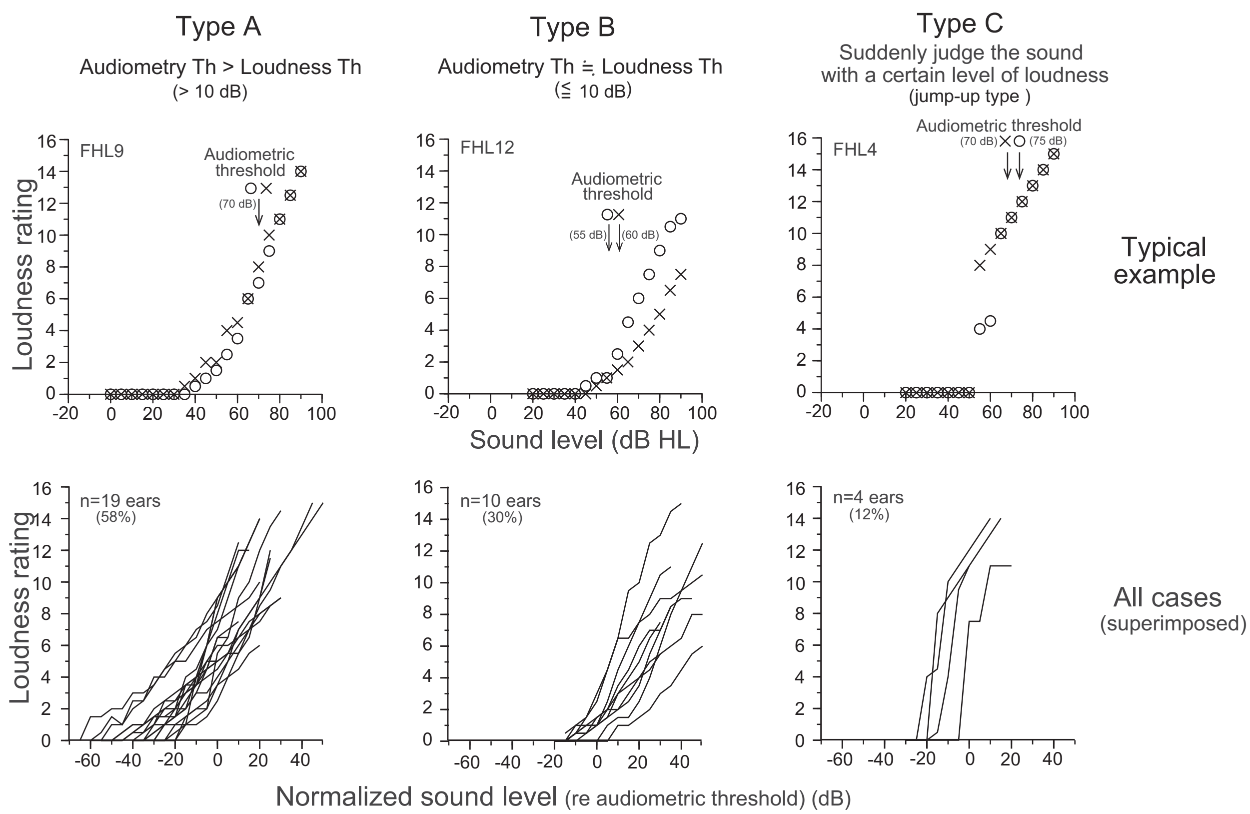

Figure 3. Three types of loudness functions obtained from patients with functional hearing loss (FHL). Type A: the threshold determined from the loudness function measurement is lower than the audiometric threshold by 10 dB or more; type B: the threshold determined from the loudness function is almost equal to the audiometric threshold (threshold difference ≤ 10 dB); type C: there is a jump in the loudness function. Upper row: typical examples (data from the right and left ears are represented as circles and crosses, respectively; arrows in the figures indicate the thresholds determined by routine audiometry). Bottom row: superimposed normalised loudness functions (normalised based on the audometric threshold) for all cases. Th: threshold.

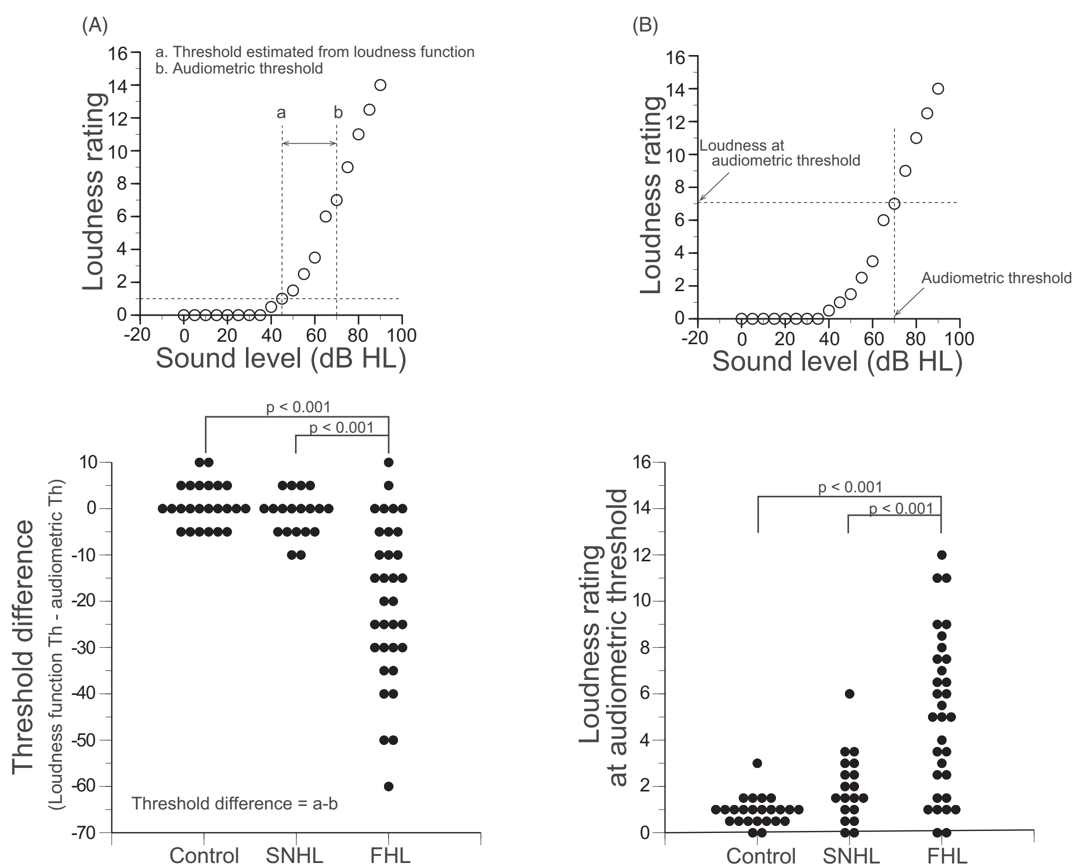

Figure 4. Comparison of the loudness functions obtained from healthy volunteers (control), patients with SNHL, and patients with FHL. (A) Difference between the threshold determined by routine audiometry and that estimated from the loudness function; (B) loudness ratings in response to a sound at the audiometric threshold level. The significance of differences between groups was determined using one-way analysis of variance with Bonferroni post-hoc analysis. Th: threshold.

occur even for healthy volunteers when they make a judgement based on a certain loudness (Rintelmann and Carhart 1964), the patients with FHL could have judged the threshold based on a certain loudness. Healthy patients and those with hearing loss due to an organic lesion respond in audiometry when they perceive a barely noticeable sound with very low loudness, whereas patients with FHL respond only when the loudness reaches a greater value than that at threshold.

The loudness functions for patients with FHL fell into three types (Figure 3), which suggest that there may not be a single pathology underlying FHL. For types A and C, the loudness ratings at audiometric threshold were higher than those for SNHL and healthy volunteers. The results for types A and C may be consistent with the above-mentioned hypothesis relating to the type V pattern in Békésy audiometry.

For type B, the loudness ratings at the audiometric threshold were as low as those for patients with SNHL and healthy volunteers. It appears that patients rated a moderate level sound as soft, despite the finding of normal ABRs for the FHL patients, indicating that the neural information about the sound delivered from the ears to the brain was basically not pathologic.

Interestingly, patients classified as type A could judge the loudness of sound deemed "inaudible" in audiometry. One of the differences between these two measurements is the instructions; in routine audiometry, the participants were instructed to respond when they detected a sound, whereas, for the loudness measurement, they were instructed to judge the loudness of the sound. The effects of these different instructions on the audiometric threshold shown in Figure 5 seem to support the idea that the "instructions or contents of task" can affect the thresholds for this group. It is uncertain why the threshold determined by loudness measurement was often lower than the audiometric threshold, but the one possible factor may be the different amount of "auditory attention" used to perform a simple detection task in normal audiometry and a more active task of judging the loudness in this group. That is, if it is hypothesised that less attention was paid to the sound in a simple detection task in normal audiometry, while the more active

Table 2. Statistical analysis on the differences between three groups (Control, SNHL and FHL) using a one-way-ANOVA with Bonferroni post-hoc analysis.

				Bonferroni post-hoc analysis		
	F test	*p* value	Effect size (η^2)	Control vs SNHL	Control vs FHL	SNHL vs FHL
Threshold difference	$F\ (2,73) = 26.524$	$p < 0.001$	0.42	$p = 1.000$	$p < 0.001$	$p < 0.001$
Loudness rating at Th	$F\ (2,73) = 23.520$	$p < 0.001$	0.39	$p = 0.501$	$p < 0.001$	$p < 0.001$

Th: threshold; SNHL: sensorineural hearing loss; FHL: functional hearing loss.

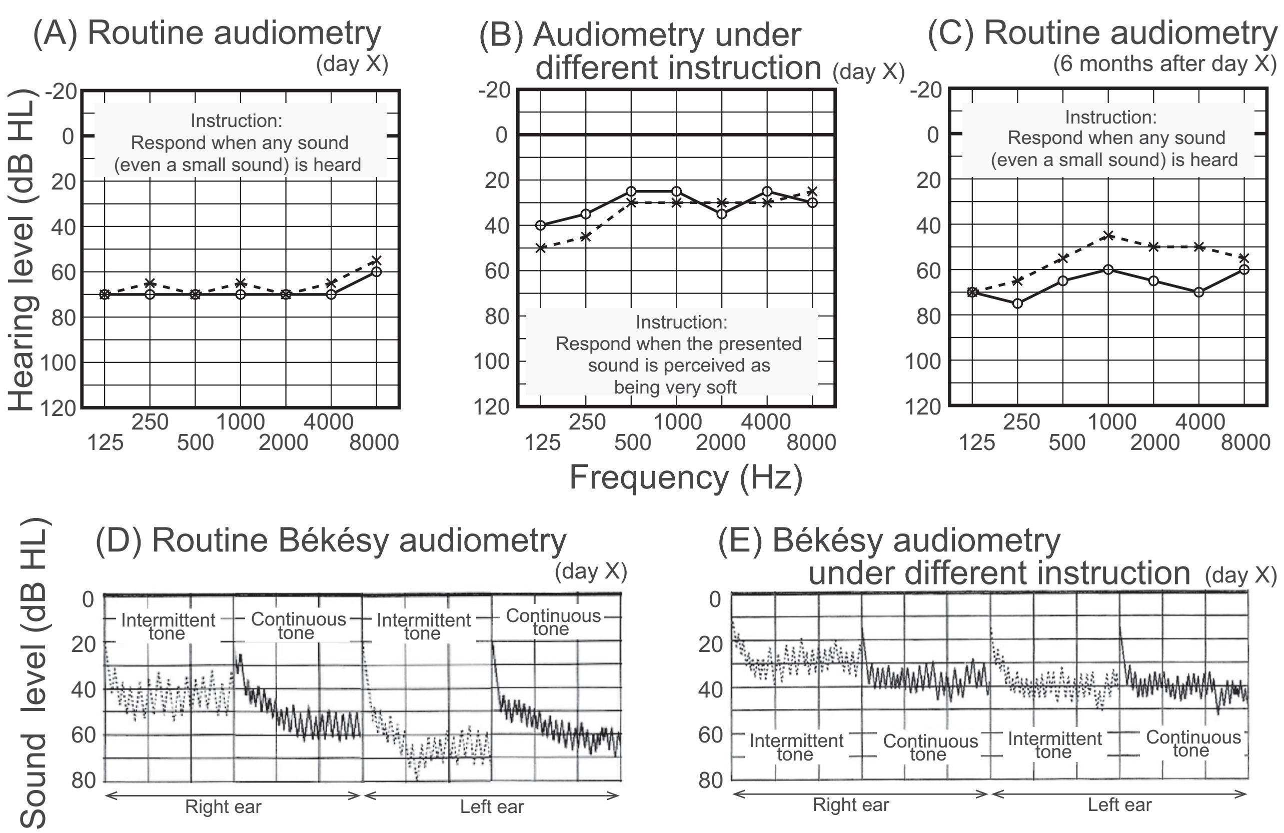

Figure 5. Audiometry and Békésy audiometry performed under different instructions for a case belonging to type A among patients with FHL. (A) Audiogram obtained under the usual instruction "respond when any sound (even a small sound) is heard"; (B) audiogram obtained under the instruction "respond when the presented sound is perceived as being very soft" (performed on the same day as audiogram A); (C) audiogram obtained under the usual instruction performed 6 months later; (D) Békésy audiometry under the usual instruction, "respond when any sound (even a small sound) is heard" (performed on the same day as audiograms A and B); (E) Békésy audiometry under the instruction "respond when the presented sound is perceived as being very soft" (performed on the same day as audiograms A and B).

task of judging loudness involved increased attention, and, as a result, the threshold to the sound may be improved. The threshold discrepancy between the audiometric threshold and the speech detection level may be considered as a similar phenomenon.

It is important to consider what factors can lead to the different loudness functions among patients with FHL. Thus far, no characteristic clinical feature has been found that could distinguish those three types (Table 1). Based on the hypothesis relating to type V Békésy audiometry, the patients were expected to be classified as types A and C, but not B. However, actual data did not always show such results (Table 1). In addition, the relationship between these types and the prognosis or the presence/absence of psychological factors is interesting, but it was difficult to draw any definitive conclusion from the present retrospective study. A further prospective study is needed to clarify the significance or meaning of the differences in the loudness function among the patients with FHL.

5. Conclusions

Loudness functions for patients with FHL were usually different from those for patients with SNHL and healthy volunteers; for about 70% of the patients with FHL, the thresholds determined from the loudness function were lower than the audiometric threshold by more than 10 dB, and/or the loudness ratings were elevated for a sound at the audiometric threshold. The loudness functions for patients with FHL support the hypothesis that patients with FHL often make threshold judgments based on a loudness greater than that at the true threshold, as suggested previously (Rintelmann and Carhart 1964; Rintelmann and Harford 1967). However, further studies are needed to clarify the significance and/or meaning of differences in the loudness functions among patients with FHL.

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Disclosure statement

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