The Journal of International Advanced Otology

J Int Adv Otol 2022; 18(1): 1–7 • DOI: 10.5152/iao.2022.21320

Original Article

The Relation of Sound Level Tolerance to Tinnitus Ears in Human

Yong Tae Cho[1,*], Yong-Hwi An[1,*], Dong Hyuk Jang[1], Dong Hyun Kim[1], Na Yeon Kim[1], Hyo Jeong Kim[1], Ji Hye Park[1], Hyun Joon Shim[1]

[1]Department of Otorhinolaryngology-Head and Neck Surgery, Nowon Eulji Medical Center, Eulji University Faculty of Medicine, Seoul, Korea

ORCID IDs of the authors: Y.T.C. 0000-0001-6454-4670, Y.-H.A. 0000-0001-8240-1673, D.H.J. 0000-0003-1678-4703, D.H.K. 0000-0003-0812-6751, N.Y.K. 0000-0002-0353-7730, H.J.K. 0000-0002-2926-1859, J.H.P. 0000-0003-0186-9050, H.J.S. 0000-0001-9719-6959.

Cite this article as: Tae Cho Y, An Y, Hyuk Jang D, et al. The relation of sound level tolerance to tinnitus ears in human. *J Int Adv Otol.* 2022;18(1):1-7.

BACKGROUND: The aim of this study was to evaluate the relationship between sound level tolerance and tinnitus in humans.

METHODS: We compared the loudness discomfort levels at 500 and 3000 Hz pure tones in 33 subjects with bilateral tinnitus and 33 subjects with unilateral tinnitus with normal and symmetric hearing thresholds and those of age- and sex-matched control subjects.

RESULTS: Both the tinnitus ears (108.18 ± 10.22 dB HL and 103.03 ± 11.04 dB HL) and non-tinnitus ears (108.94 ± 12.61 dB HL and 104.24 ± 11.60 dB HL) in the unilateral tinnitus subjects showed significantly lower loudness discomfort levels at 500 and 3000 Hz than the control ears (115.91 ± 6.78 dB HL and 111.52 ± 8.88 dB HL, $P < .008$; $\alpha = 0.05/6 = 0.008$), whereas there was no difference in the loudness discomfort levels of the tinnitus ears of the bilateral tinnitus subjects (111.52 ± 10.42 dB HL or 106.36 ± 11.34 dB HL) and the control ears.

CONCLUSION: These results support the hypothesis that the reduced loudness discomfort levels in tinnitus subjects with normal and symmetric hearing thresholds are associated with a hidden injury to the cochlea that induces the development of tinnitus, especially on one side. Whether tinnitus is perceived unilaterally or bilaterally depends on the status of the auditory system, which may be reflected in the sound level tolerance and loudness discomfort levels.

KEYWORDS: Hyperacusis, loudness discomfort level, sound level tolerance, tinnitus

INTRODUCTION

Many people with tinnitus show an increased sensitivity to sound called "hyperacusis." The prevalence rates of hyperacusis in people without tinnitus are 8-15%,[1,2] whereas they are 18-38% in people with tinnitus.[3-5] Moreover, the majority of hyperacusis patients (86%) report tinnitus.[6] The high prevalence of comorbid tinnitus and hyperacusis implies a relationship between sound level tolerance and tinnitus. Hébert et al[7] demonstrated that sound level tolerance was lower in tinnitus subjects compared with that in non-tinnitus subjects who were carefully matched for hearing level. They also found that this increased sensitivity to sound was particularly pronounced in ears with normal audiograms, presumably because the reduced compression functions in the damaged auditory system mask the effects of tinnitus itself. A similar finding was reported in another study in which the average loudness discomfort levels (LDLs) was 11.3 dB lower in adolescents with normal hearing and tinnitus (or previous tinnitus) than in adolescents with normal hearing and no tinnitus.[8] The LDL in tinnitus subjects is suggested to predict the severity of tinnitus,[7] given that the severity of tinnitus increases in the presence of hyperacusis.[9,10] Therefore, some have hypothesized that hyperacusis and tinnitus result from the same mechanism, which is a compensatory increase in central gain and hyperactivity induced by reduced sensory input.[5,11-13] However, there is also evidence that does not fit the common origin theory of tinnitus and hyperacusis. Although a majority of hyperacusis patients report tinnitus,[6] the reverse is not true. Sheldrake et al[14] reported that LDLs indicating hyperacusis tended to be slightly higher at frequencies at which hearing loss was present, whereas tinnitus usually develops at frequencies with hearing loss. The LDLs of hyperacusis subjects are reduced across the full range of audiometric frequencies, indicating a certain generalized frequency-independent distortion. In contrast, tinnitus is thought to be caused in a restricted frequency range.[15] In previous studies, we found that the LDLs of both the tinnitus ears (TEs) and non-tinnitus ears (NTEs) of unilateral tinnitus subjects with normal audiograms were lower than those of the control ears, whereas there was no significant difference in the LDLs of TEs and NTEs.[16,17]

*Yong Tae Cho and Yong-Hwi An contributed equally to this work.
Corresponding author: Hyun Joon Shim, e-mail: eardoc11@naver.com

Received: April 8, 2021 • **Accepted:** May 28, 2021
Available online at www.advancedotology.org

To investigate the relationship between sound level tolerance and tinnitus, we compared the LDLs of tinnitus and non-tinnitus subjects. Although previous studies by other authors have compared the LDLs of mixed groups of subjects with unilateral or bilateral tinnitus and those of control groups,[7,8] we assumed that separate comparisons of unilateral tinnitus subjects and bilateral tinnitus subjects with control subjects would clarify the relationship between sound level tolerance and tinnitus precisely. Moreover, a comparison of the LDLs of unilateral tinnitus subjects and bilateral tinnitus subjects should be useful in clarifying why NTEs as well as TEs showed lower LDLs than the control ears in our previous studies.[16,17] Subjects with sensorineural hearing loss may experience "loudness recruitment" caused by reduced compression in the damaged auditory system, so their hearing impairment masks the effect of tinnitus on sound level tolerance. Therefore, we enrolled subjects with unilateral or bilateral tinnitus and normal symmetric hearing thresholds.

METHODS

Subjects

We included 33 subjects with bilateral tinnitus (12 males: 35.00 ± 12.80 years; 21 females: 39.00 ± 13.13 years) and 33 subjects with unilateral tinnitus (12 males: 35.17 ± 13.07 years; 21 females: 39.29 ± 12.60 years) and normal and symmetric hearing thresholds (≤20 dB HL at 0.25, 0.5, 1, 2, 3, 4, and 8 kHz and a binaural difference of ≤10 dB at all the frequencies measured). We also enrolled age- and sex-matched control subjects (12 males: 35.42 ± 13.43 years; 21 females: 39.05 ± 12.49 years) with normal and symmetric hearing thresholds (the same criteria used for the tinnitus group). The mean pure tone averages (PTAs) of the bilateral tinnitus subjects were 6.55 ± 4.25 dB HL in the right ears and 5.80 ± 5.06 dB HL in the left ears. The mean PTAs of the unilateral tinnitus subjects were 7.46 ± 4.46 dB HL in the TEs and 6.33 ± 4.07 dB HL in the NTEs (Table 1). The mean PTAs of the control subjects were 7.98 ± 4.02 dB HL in the right ears and 7.44 ± 5.35 dB HL in the left ears.

After careful physical examination of the head and neck regions of each participant, we excluded those suspected of having objective tinnitus or somatic tinnitus from the study. Subjects with chronic otitis media, a retrocochlear lesion, endolymphatic hydrops, or congenital ear malformation were also excluded. Ethical committee approval was received from the Nowon Eulji Medical Center (EMCIRB 17 - 115). Written informed consent was obtained from all participants who participated in this study.

Procedure

We made separate psychoacoustic measurements of LDL with 500 and 3000 Hz pure tones in both ears of the bilateral tinnitus subjects and in the TEs and NTEs of the unilateral tinnitus subjects. The stimuli were routed through an audiometer (AC40, Interacoustics, Middelfart, Denmark) and presented monaurally to each test ear via headphones (TDH-39P, Telephonics, Farmingdale, NY, USA). We explained to the subjects about measuring LDL as follows: "You will gradually hear loud sounds through headphones. If you feel uncomfortable with the sound, press the button immediately." The measurement of LDL was commenced at 60 dB HL and increased in 5 dB steps until the subject indicated that the signal level was uncomfortable. If subjects did not feel uncomfortable at 115 dB HL, we recorded LDL as 120 dB HL.

Analysis

In the bilateral tinnitus subjects and the control subjects, one side (either left or right) was randomly selected and designated the representative ear of the bilateral tinnitus subjects and a control ear, respectively. Statistical comparisons of the average LDLs among the representative ears of the bilateral tinnitus subjects, the TEs and NTEs of the unilateral tinnitus subjects, and the control ears of the

Table 1. Demographics and Characteristics of Tinnitus Subjects With Bilateral and Unilateral Tinnitus Subjects

	Bilateral (n = 33)		**Unilateral (n = 33)**		***P***
Age (years)	37.50 ± 12.95		37.22 ± 12.73		ns
Sex (male:female)	4:7		4:7		ns
PTA (dB hearing level)	Right ear	Left ear	Tinnitus ears	Non-tinnitus ears	
	6.55 ± 4.25	5.80 ± 5.06	7.46 ± 4.46	6.33 ± 4.07	ns
Duration (month)	10.88 ± 23.17		5.09 ± 12.30		ns
Hyperacusis (n)	With hyperacusis	Without hyperacusis	With hyperacusis	Without hyperacusis	
	5	28	10	13	ns
Psychoacoustic measurements of tinnitus					
Pitch (kHz)	5.46 ± 3.31		3.39 ± 2.86		ns
Loud (dB SL)	5.75 ± 3.99		6.53 ± 4.93		ns
MML (dB SL)	10.64 ± 8.04		17.17 ± 17.54		ns
Questionnaires					
THI	39.91 ± 24.29		34.88 ± 23.15		ns
VAS	4.67 ± 2.29		4.72 ± 2.07		ns
TAS (%)	55.76 ± 34.64		44.06 ± 32.71		ns
BDI	13.63 ± 9.14		11.28 ± 6.57		ns

PTA, pure tone average; MML, minimal masking level; THI, tinnitus handicap inventory; VAS, visual analogue scale; TAS, tinnitus awareness score; BDI, Beck Depression Inventory; ns, not significant ($P > .05$).

normal subjects were made with multiple independent *t* tests and paired *t* tests with the Bonferroni correction ($\alpha = 0.05/6 = 0.008$). The Kruskal–Wallis test and Mann–Whitney test with the Bonferroni correction were used to evaluate the comparisons among TEs (NTEs) with hyperacusis, TEs (NTEs) without hyperacusis, and control ears and the comparisons of improved subjects, unimproved subjects, and control subjects. Correlations between the LDLs at 500 and 3000 Hz and the characteristics of tinnitus were analyzed with Pearson's correlation analysis or Spearman's correlation analysis.

RESULTS

Characteristics of Tinnitus in Bilateral and Unilateral Tinnitus Subjects

The mean duration of tinnitus did not differ significantly between the unilateral and bilateral tinnitus subjects (n = 33 in each group, 5.09 ± 12.30 months vs. 10.88 ± 23.17 months, respectively; $P > .05$). The psychoacoustic measurements of tinnitus, including the loudness, pitch, and minimal masking level, did not differ between the unilateral and bilateral tinnitus subjects (all $P > .05$) (Table 1). There were no significant differences between the unilateral and bilateral tinnitus subjects in the Tinnitus Handicap Inventory score, a visual analogue scale of tinnitus loudness (10-point scale), the tinnitus awareness score (percentage of time the patient was aware of tinnitus in 1 day), or the Beck Depression Inventory determined with an initial questionnaire (all $P > .05$) (Table 1). In a subgroup analysis of the bilateral tinnitus subjects, there was no difference in the characteristics of tinnitus among the subjects who had the same loudness in both ears (n = 12), who had right dominant tinnitus (n = 9), or who had left dominant tinnitus (n = 11). One of the bilateral tinnitus subjects had a different type of tinnitus at each side.

Comparisons of LDLs at 500 and 3000 Hz in TEs of Bilateral Tinnitus Subjects, TEs and NTEs of Unilateral Tinnitus Subjects, and Control Ears

Multiple comparisons with the Bonferroni correction revealed that the TEs (n = 33, 108.18 ± 10.22 dB HL) and NTEs (n = 33, 108.94 ± 12.61 dB HL) in the unilateral tinnitus subjects showed significantly lower LDLs at 500 Hz than the control ears (n = 33, 115.91 ± 6.78 dB HL; TEs vs. control ears, $t(64) = -3.62$, $P = .001$; NTEs vs. control ears, $t(64) = -2.80$, $P = 0.007$; $\alpha = 0.05/6 = 0.008$; Figure 1). We also detected lower LDLs at 3000 Hz for TEs (103.03 ± 11.04 dB HL) and NTEs (104.24 ± 11.60 dB HL) in the unilateral tinnitus subjects than in the control ears (111.52 ± 8.88; TEs vs. control ears, $t(64) = -3.44$, $P = .001$; NTEs vs. control ears; $t(64) = -2.86$, $P = .006$; Figure 1). However, there were no significant differences between the TEs of the bilateral tinnitus subjects and the control ears in the LDLs at 500 or 3000 Hz (111.52 ± 10.42 dB HL or 106.36 ± 11.34 dB HL, respectively; $P > .05/6$; Figure 1). A within-subject comparison between the TEs and NTEs of the unilateral tinnitus subjects detected no significant differences in the LDLs at 500 or 3000 Hz ($P > .05/6$; Figure 1).

Comparisons of Tinnitus Characteristics and LDLs of TEs (or NTEs) Without Hyperacusis and TEs (or NTEs) With Hyperacusis

Of the bilateral and unilateral tinnitus subjects, 51 (20 males, 31 females; 38.00 ± 13.24 years) had no hyperacusis and 15 (4 males, 11 females; 36.47 ± 11.22 years) complained of hyperacusis. The duration of tinnitus, the psychoacoustic measurements of tinnitus, and the results of the tinnitus questionnaire did not differ between the tinnitus subjects with and without hyperacusis ($P > .05$) (Table 2).

The Mann–Whitney test with the Bonferroni correction revealed that in the tinnitus subjects, the TEs without hyperacusis (110.59 ± 9.73 dB HL and 105.98 ± 10.77 dB HL) and the TEs with hyperacusis (107.33 ± 12.37 dB HL and 100.33 ± 12.02 dB HL) showed significantly lower LDLs at 500 and 3000 Hz, respectively, than the control ears (500 Hz, $U = 538.0$ and 117.0, $P = .003$ and .002, respectively; 3000 Hz, $U = 574.0$ and 112.0, $P = .012$ and .002, respectively; $\alpha = 0.05/3$; Figure 2). However, there were no differences at 500 or 3000 Hz between the TEs without hyperacusis and those with hyperacusis ($P > .05/3$; Figure 2). The Mann–Whitney test with the Bonferroni correction showed that only NTEs with hyperacusis (105.50 ± 11.89 dB HL and 101.00 ± 9.66 dB HL) showed significantly lower LDLs than the control ears at 500 and 3000 Hz, respectively (500 Hz, $U = 73.5$, $P = .004$; 3000 Hz, $U = 66.0$, $P = 0.004$; $\alpha = 0.05/3$; Figure 3). There were no significant differences in the LDLs at 500 or 3000 Hz between the NTEs with hyperacusis and those without hyperacusis ($P > .05/3$).

Comparisons of Tinnitus Characteristics and LDLs in Unimproved Subjects and Improved Subjects

There were 27 unimproved subjects (13 males, 14 females; 37.85 ± 11.82 years) and 39 improved subjects (11 males, 28 females; 37.50 ± 13.50 years) among the total subjects with tinnitus. Improvement was defined as a reduction of >20 points in the Tinnitus Handicap Inventory score, a reduction of >2 points in the visual analogue scale

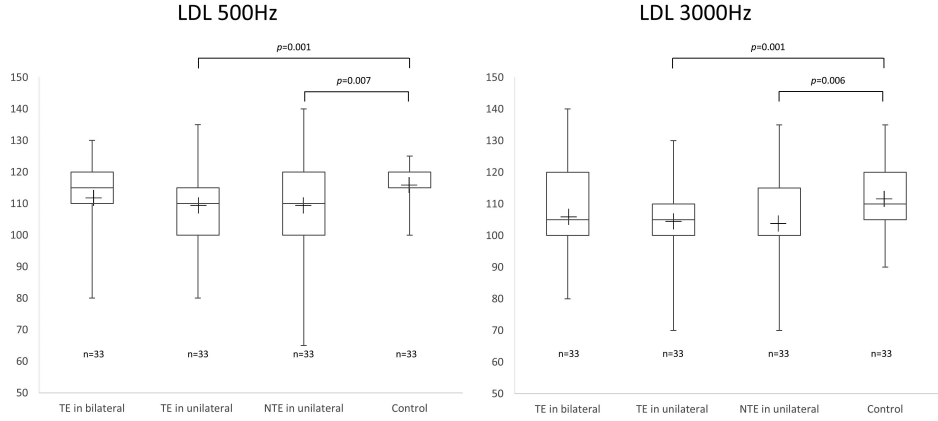

Figure 1. Comparisons of LDLs at 500 and 3000 Hz among the TEs of bilateral tinnitus subjects, the TEs and NTEs of unilateral tinnitus subjects, and the control ears. LDL, loudness discomfort level; TEs, tinnitus ears; NTEs, non-tinnitus ears.

Table 2. Demographics and Characteristics of Tinnitus Subjects With Hyperacusis and Without Hyperacusis

	Without Hyperacusis (n = 51)	With Hyperacusis (n = 15)	*P*
Age (years)	38.00 ± 13.24	36.47 ± 11.22	ns
Sex (male:female)	20:31	4:11	ns
Duration (month)	6.63 ± 15.16	12.60 ± 27.60	ns
Psychoacoustic measurements of tinnitus			
Pitch (kHz)	5.00 ± 3.32	2.86 ± 2.54	ns
Loud (dB SL)	5.82 ± 4.46	7.14 ± 4.06	ns
MML (dB SL)	14.36 ± 14.46	9.75 ± 3.59	ns
Questionnaires			
THI	35.16 ± 24.59	45.00 ± 19.21	ns
VAS	4.62 ± 2.30	4.93 ± 1.67	ns
TAS (%)	47.60 ± 33.48	58.00 ± 35.50	ns
BDI	11.35 ± 7.67	16.07 ± 8.16	ns

PTA, pure tone average; MML, minimal masking level; THI, tinnitus handicap inventory; VAS, visual analogue scale; TAS, tinnitus awareness score; BDI, Beck depression inventory; ns, not significant ($P > .05$).

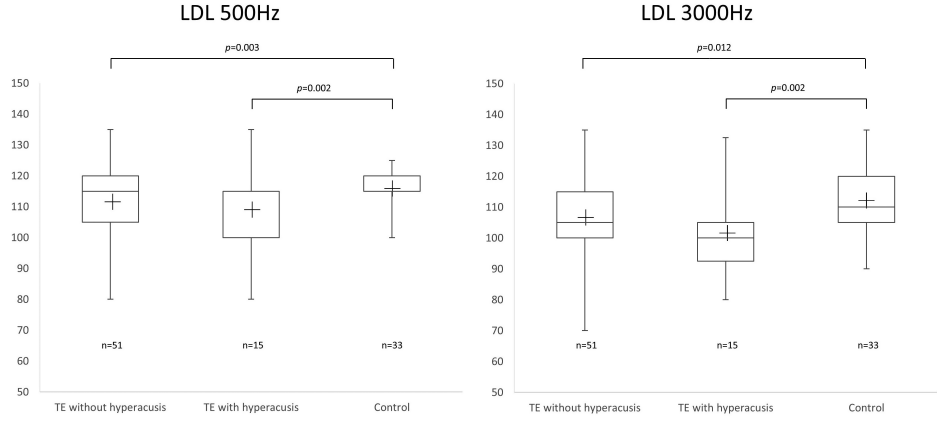

Figure 2. Comparisons of LDLs at 500 and 3000 Hz among the TEs with hyperacusis, TEs without hyperacusis, and control ears. LDL, loudness discomfort level; TEs, tinnitus ears; NTEs, non-tinnitus ears.

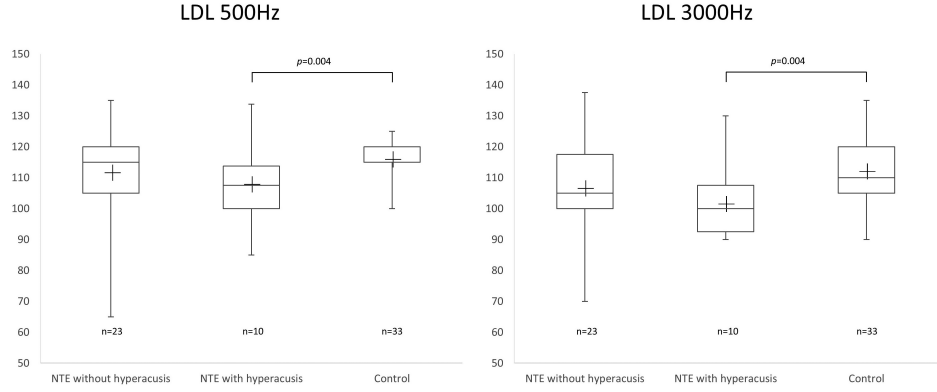

Figure 3. Comparisons of LDLs at 500 and 3000 Hz among the NTEs with hyperacusis, NTEs without hyperacusis, and control ears. LDL, loudness discomfort level; TEs, tinnitus ears; NTEs, non-tinnitus ears.

of tinnitus loudness, or a reduction of >10% in the tinnitus awareness score 1 month after oral treatment with alprazolam (0.25 mg/day). The duration of tinnitus, the psychoacoustic measurements of tinnitus, and the results of the tinnitus questionnaire did not differ between tinnitus subjects with and without hyperacusis (all $P > .05$) (Table 3).

The Mann–Whitney test with the Bonferroni correction showed that the TEs of the unimproved subjects (500 Hz, 109.63 ± 9.40 dB HL; 3000 Hz, 104.07 ± 10.38 dB HL) and the improved subjects (500 Hz, 110.00 ± 11.12 dB HL; 3000 Hz, 105.13 ± 11.89 dB HL) had significantly lower LDLs at 500 and 3000 Hz than the controls (500 Hz, $U = 246.5$ and 408.5, $P = .002$ and .005, respectively; 3000 Hz, $U = 255.5$ and 430.5,

Table 3. Demographics and Characteristics of Unimproved Subjects and Improved Subjects

	Unimproved Subjects (n = 27)	Improved Subjects (n = 39)	*P*
Age (years)	37.85 ± 11.82	37.50 ± 13.50	ns
Sex (male:female)	13:14	11:28	ns
Duration (month)	6.48 ± 11.91	9.03 ± 22.23	ns
Psychoacoustic measurements of tinnitus			
Pitch (kHz)	5.24 ± 3.35	3.95 ± 3.14	ns
Loud (dB SL)	5.47 ± 3.45	6.67 ± 5.11	ns
MML (dB SL)	16.33 ± 17.29	11.36 ± 9.00	ns
Questionnaires			
THI	44.44 ± 28.97	32.45 ± 17.87	ns
VAS	4.85 ± 2.11	4.58 ± 2.23	ns
TAS (%)	56.30 ± 33.07	45.53 ± 34.30	ns
BDI	12.93 ± 7.56	12.11 ± 8.36	ns

PTA, pure tone average; MML, minimal masking level; THI, tinnitus handicap inventory; VAS, visual analogue scale; TAS, tinnitus awareness score; BDI, Beck Depression Inventory; ns, not significant ($P > .05$).

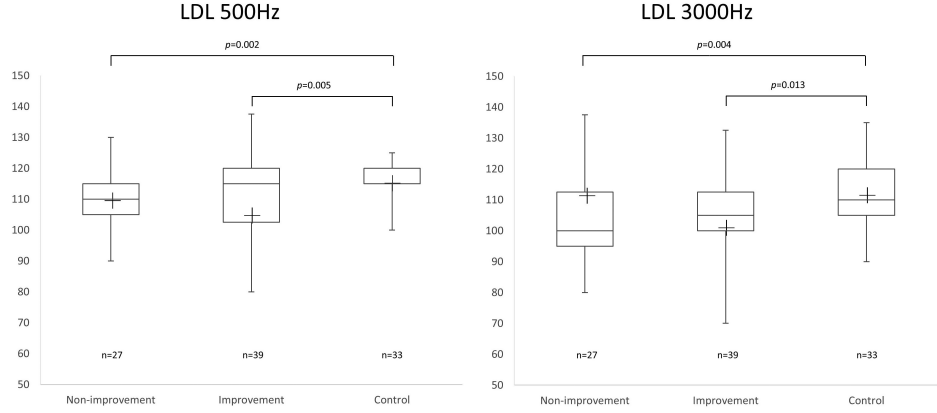

Figure 4. Comparisons of LDLs at 500 and 3000 Hz among the unimproved subjects, improved subjects, and control subjects.

$P = .004$ and .013, respectively; $\alpha = 0.05/3$; Figure 4). There were no differences in the LDLs at 500 or 3000 Hz between the TEs of the unimproved subjects and improved subjects ($P > .05/3$).

Correlation Analyses

The LDLs at 500 and 3000 Hz showed no correlation with the duration of tinnitus, any psychoacoustic measurement, or the results of the questionnaire.

DISCUSSION

To evaluate the effect of tinnitus on sound level tolerance, we applied the following strict inclusion criteria to the subjects: a hearing threshold of ≤20 dB and symmetric hearing (within ≤10 dB) at any measured frequency. We assumed that ears with normal and symmetric hearing would ensure similar sound compression in the ear affecting sound level tolerance in within-subject comparisons (TE vs. NTE) or between-subject comparisons. Therefore, in this setting, the difference in LDL that depended on the presence or absence of tinnitus was mainly attributed to the effect of tinnitus.

We found that the TEs and NTEs of unilateral tinnitus subjects showed significantly lower LDLs than the control ears, consistent with our previous study,[16,17] whereas there was no difference in the LDLs of the TEs of bilateral tinnitus subjects and the control ears. To explain these findings, we proposed several hypotheses. First, the increased sensitivity to sound in tinnitus subjects with normal and symmetric hearing thresholds could be associated with unknown personal factors or with a hidden injury to the cochlea-like cochlear synaptopathy[18] that induced tinnitus, rather than with tinnitus itself. Sanchez et al[8] argued that adolescents with normal audiograms and reduced LDLs could have hidden synaptic injuries, which are prevalent among adolescents, and may be vulnerable to subsequent exposure to high-level environmental sounds. Second, hyperacusis and tinnitus result from the same mechanism, that is, a compensatory increase in central gain and hyperactivity induced by reduced sensory input.[11,12] Zeng[13] proposed the active loudness model to explain the close association between the mechanisms underlying hyperacusis and tinnitus. Reduced auditory input increases the nonlinear gain to enhance loudness perception, which may introduce an unbalanced state in the brain, requiring it to increase the central noise level to restore this balance and thus producing tinnitus. Third, tinnitus could be a cause of increased sensitivity to sound in these subjects. Tinnitus may function as a central masker, reducing audibility, and the compensatory increase in central gain could decrease sound level tolerance.

We used these results to test our 3 hypotheses that were described in the introduction to explain the relationship between sound level tolerance and tinnitus. Our first hypothesis is that the reduced LDL in tinnitus subjects with normal and symmetric hearing thresholds is associated with a hidden injury to the cochlea that induced the tinnitus. There may be subjects with hidden damage to their auditory systems and sound-level intolerance despite normal hearing thresholds, and their auditory systems will be vulnerable to subsequent damage, causing unilateral tinnitus. Relatively weak damage to the cochlea by a hidden injury, indicated by a low LDL, might lead to tinnitus perceived in a unilateral hemisphere. However, severe damage is required to develop tinnitus on the intact cochlea, indicated by a normal LDL, and this severe damage may cause tinnitus in both hemispheres.

In relation to the second hypothesis, that hyperacusis and tinnitus result from the same mechanism, the results suggest that increased central gain can lead to unilateral tinnitus but not to bilateral tinnitus. This seems to indicate that unilateral tinnitus and bilateral tinnitus have different pathophysiologies, although this is unlikely for the following reasons. First, there were no differences in the subjective or objective characteristics of tinnitus in the subjects with unilateral or bilateral tinnitus. Second, in this study, the nature of the tinnitus sounds perceived in both ears was the same as in the 33 bilateral tinnitus subjects, except in 1 case. Third, in a subgroup analysis of the bilateral tinnitus subjects, there were no differences in the LDLs or characteristics of tinnitus among the subjects who experienced the same loudness in both ears, who had right dominant tinnitus or who had left dominant tinnitus. These findings suggest that tinnitus can be perceived in a unilateral hemisphere or bilateral hemispheres after it is triggered by cochlear damage on 1 side. In relation to the third hypothesis, that tinnitus is a central masker that causes increased sensitivity to sound, we must explain why unilateral tinnitus has a stronger masking effect than bilateral tinnitus, but this is improbable. Therefore, the results in this study support the first hypothesis that the reduced LDLs in tinnitus subjects with normal and symmetric hearing thresholds are associated with a hidden injury to the cochlea that induces the development of tinnitus, especially on one side.

Recent neuroimaging studies have provided evidence of differences in the neural activity associated with unilateral and bilateral tinnitus. Compared with bilateral tinnitus, unilateral tinnitus evokes increased gamma-band activity in the contralateral parahippocampal area and the primary and secondary auditory cortices on quantitative electroencephalography.[19] Unlike unilateral tinnitus, bilateral tinnitus is associated with delta activity in the ventrolateral prefrontal cortex. The authors hypothesized that a change in the activation of the parahippocampal area to unilateral activation from the default mode of bilateral activation could result in unilateral tinnitus, given that an external sound normally elicits bilateral parahippocampal activation.[20,21] In neuroimaging studies using functional magnetic resonance imaging,[22,23] unilateral tinnitus subjects showed abnormally small signal changes in the brain contralateral to the tinnitus perception, whereas bilateral tinnitus subjects showed symmetric response. Given that bilateral tinnitus is usually initiated from the unilateral perception of tinnitus and the central auditory pathway innervates both hemispheres, tinnitus can be perceived in a unilateral hemisphere or bilateral hemispheres after it is triggered by cochlear damage on one side. The laterality of tinnitus is determined by the plasticity of the brain and is presumably affected by the status of the auditory system, such as the presence of hidden damage or the effect of the damage. The amount of damage present (weak or severe) may also determine the laterality of tinnitus.

It is assumed that the lower LDLs in NTEs as well as TEs relative to those in the control ears arise from the loudness balance mechanism controlled by the lateral olivocochlear efferents. This mechanism could increase the loudness sensitivity of the NTE to the level of the TE. There is evidence that the lateral olivocochlear efferents balance the cochlear nerve output between the 2 ears for accurate sound localization, based on interaural level differences in human and animal studies.[24,25]

In this study, the proportion of tinnitus subjects who complained of subjective hyperacusis was 22.7%, which is similar to the rates in other studies. Unexpectedly, there was no difference in the LDLs of subjects with and without hyperacusis, which may be attributable to the mild hyperacusis symptoms reported. The average LDLs at 500 and 3000 Hz for TEs with hyperacusis were 107.33 and 100.33 dB HL, respectively and were far from the suggested criteria for a diagnosis of hyperacusis in other studies of 80,[26] 77,[27] and 70 dB HL.[6] In the present study, all the subjects attended the clinic with a primary complaint of tinnitus and were asked whether they also experienced hyperacusis symptoms. Loudness discomfort levels and the corresponding level of sound intolerance may differ greatly between patients with a primary complaint of tinnitus and accompanying hyperacusis and patients with a primary complaint of hyperacusis. Previous studies have demonstrated reduced LDLs in tinnitus subjects with normal audiograms compared with those in normal subjects, with differences in LDL of <10 dB[7,16,17] or 11.3 dB,[6] which are consistent with the results presented here. Accompanying hyperacusis did not seem to affect the pathophysiology of tinnitus because there were no differences in the LDLs or subjective or objective characteristics of tinnitus in subjects with and without hyperacusis. We believe that a reduction in LDL of about 10 dB can be experienced as hyperacusis in a minority of tinnitus subjects but is not experienced as hyperacusis in the majority of tinnitus subjects. The lack of differences in the LDLs or the characteristics of tinnitus in improved and unimproved subjects implies that low LDLs are a risk factor for tinnitus but are not related to its prognosis.

CONCLUSION

Only unilateral tinnitus subjects with normal and symmetric hearing thresholds, and not bilateral tinnitus subjects with normal and symmetric hearing thresholds, showed greater sensitivity to sound than non-tinnitus subjects. This result may imply that damage to the cochlea with a hidden injury, indicated by a low LDL, might lead to tinnitus that is perceived in a unilateral hemisphere. Whether tinnitus is perceived unilaterally or bilaterally depends on the status of the auditory system, which may be reflected in the sound level tolerance and LDL.

Ethics Committee Approval: Ethical committee approval was received from the Nowon Eulji Medical Center (EMCIRB 17 - 115).

Informed Consent: Written informed consent was obtained from all participants who participated in this study.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – H.J.S.; Design – H.J.S., Y.A.; Supervision – H.J.S.; Resources – D.H.K., N.Y.K., H.J.K., J.H.P.; Materials – D.H.K., N.Y.K., H.J.K., J.H.P.; Data Collection and/or Processing – Y.T.C., D.H.J.; Analysis and/or Interpretation – Y.T.C., D.H.J.; Literature Search – Y.T.C.; Writing Manuscript – Y.T.C., Y.A., H.J.S.; Critical Review – H.J.S.

Acknowledgments: The authors would like to thank Hye Young Han from Nowon Eulji Medical Center Library for manuscript's technical editing.

Conflict of Interest: The authors have no conflicts of interest to declare.

Financial Disclosure: This work was supported by EMBRI Grants 2019 SN0002 from the Eulji University.

REFERENCES

1. Andersson G, Lindvall N, Hursti T, Carlbring P. Hypersensitivity to sound (hyperacusis): a prevalence study conducted via the internet and post. *Int J Audiol*. 2002;41(8):545-554. [CrossRef]
2. Fabijanska A, Rogowski M, Bartnik G, Skarzynski H. Epidemiology of tinnitus and hyperacusis in Poland. In: *Proceedings of the Sixth International Tinnitus Seminar*. Citeseer; 1999:569-571.
3. Guimarães AC, Carvalho GM, Voltolini MM, et al. Study of the relationship between the degree of tinnitus annoyance the presence of hyperacusis. *Braz J Otorhinolaryngol*. 2014;80(1):24-28. [CrossRef]
4. Park SN, Yeo SW, Cho CE, et al. Hyperacusis in patients with tinnitus-audiometrical evaluation and clinical characterization. *Korean J Otolaryngol Head Neck Surg*. 2002;45:946-951.
5. Hébert S, Canlon B, Hasson D. Emotional exhaustion as a predictor of tinnitus. *Psychother Psychosom*. 2012;81(5):324-326. [CrossRef]
6. Anari M, Axelsson A, Eliasson A, Magnusson L. Hypersensitivity to sound--questionnaire data, audiometry and classification. *Scand Audiol*. 1999;28(4):219-230. [CrossRef]
7. Hébert S, Fournier P, Noreña A. The auditory sensitivity is increased in tinnitus ears. *J Neurosci*. 2013;33(6):2356-2364. [CrossRef]
8. Sanchez TG, Moraes F, Casseb J, Cota J, Freire K, Roberts LE. Tinnitus is associated with reduced sound level tolerance in adolescents with normal audiograms and otoacoustic emissions. *Sci Rep*. 2016;6:1-8.
9. Fioretti AB, Fusetti M, Eibenstein A. Association between sleep disorders, hyperacusis and tinnitus: evaluation with tinnitus questionnaires. *Noise Health*. 2013;15(63):91-95. [CrossRef]
10. Hiller W, Goebel G. Factors influencing tinnitus loudness and annoyance. *Arch Otolaryngol Head Neck Surg*. 2006;132(12):1323-1330. [CrossRef]
11. Noreña AJ, Chery-Croze S. Enriched acoustic environment rescales auditory sensitivity. *NeuroReport*. 2007;18(12):1251-1255. [CrossRef]
12. Noreña AJ. An integrative model of tinnitus based on a central gain controlling neural sensitivity. *Neurosci Biobehav Rev*. 2011;35(5):1089-1109. [CrossRef]
13. Zeng FG. An active loudness model suggesting tinnitus as increased central noise and hyperacusis as increased nonlinear gain. *Hear Res*. 2013;295:172-179. [CrossRef]
14. Sheldrake J, Diehl PU, Schaette R. Audiometric characteristics of hyperacusis patients. *Front Neurol*. 2015;6:105. [CrossRef]
15. Schecklmann M, Vielsmeier V, Steffens T, Landgrebe M, Langguth B, Kleinjung T. Relationship between Audiometric slope and tinnitus pitch in tinnitus patients: insights into the mechanisms of tinnitus generation. *PLoS ONE*. 2012;7(4):e34878. [CrossRef]
16. Shim HJ, An YH, Kim DH, Yoon JE, Yoon JH. Comparisons of auditory brainstem response and sound level tolerance in tinnitus ears and non-tinnitus ears in unilateral tinnitus patients with normal audiograms. *PLoS ONE*. 2017;12(12):e0189157. [CrossRef]
17. Shim HJ, Cho YT, Oh HS, An YH, Kim DH, Kang YS. Within-subject comparisons of the auditory brainstem response and uncomfortable loudness levels in ears with and without tinnitus in unilateral tinnitus subjects with normal audiograms. *Otol Neurotol*. 2021;42:10-17.
18. Kujawa SG, Liberman MC. Adding insult to injury: cochlear nerve degeneration after "temporary" noise-induced hearing loss. *J Neurosci*. 2009;29(45):14077-14085. [CrossRef]
19. Vanneste S, Plazier M, van der Loo E, Van de Heyning P, De Ridder D. The difference between uni- and bilateral auditory phantom percept. *Clin Neurophysiol*. 2011;122(3):578-587. [CrossRef]
20. Mayer AR, Hanlon FM, Franco AR, et al. The neural networks underlying auditory sensory gating. *Neuroimage*. 2009;44(1):182-189. [CrossRef]
21. Wang Z, Mechanic-Hamilton D, Pluta J, Glynn S, Detre JA. Function lateralization via measuring coherence laterality. *Neuroimage*. 2009;47(1):281-288. [CrossRef]
22. Melcher JR, Sigalovsky IS, Guinan JJ Jr, Levine RA. Lateralized tinnitus studied with functional magnetic resonance imaging: abnormal inferior colliculus activation. *J Neurophysiol*. 2000;83(2):1058-1072. [CrossRef]
23. Smits M, Kovacs S, de Ridder D, Peeters RR, van Hecke P, Sunaert S. Lateralization of functional magnetic resonance imaging (fMRI) activation in the auditory pathway of patients with lateralized tinnitus. *Neuroradiology*. 2007;49(8):669-679. [CrossRef]
24. Munro KJ, Turtle C, Schaette R. Plasticity and modified loudness following short-term unilateral deprivation: evidence of multiple gain mechanisms within the auditory system. *J Acoust Soc Am*. 2014;135(1):315-322. [CrossRef]
25. Darrow KN, Maison SF, Liberman MC. Cochlear efferent feedback balances interaural sensitivity. *Nat Neurosci*. 2006;9(12):1474-1476. [CrossRef]
26. Sherlock LP, Formby C. Estimates of loudness, loudness discomfort, and the auditory dynamic range: normative estimates, comparison of procedures, and test-retest reliability. *J Am Acad Audiol*. 2005;16(2):85-100. [CrossRef]
27. Aazh H, Moore BCJ. Factors related to uncomfortable loudness levels for patients seen in a tinnitus and hyperacusis clinic. *Int J Audiol*. 2017;56(10):793-800. [CrossRef]