Tinnitus Is Associated With Extended High-frequency Hearing Loss and Hidden High-frequency Damage in Young Patients

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**Objectives:** To analyze the results of extended high-frequency (EHF) and high-frequency hearing tests in young patients with tinnitus who show normal response in conventional pure-tone audiometry (PTA), and to explore the correlation between tinnitus and hearing loss (HL).

**Study Design:** A case–control study.

**Setting:** A Tertiary Eye Ear Nose & Throat Hospital of China.

**Participants:** Patients with tinnitus, aged 18 to 35 years old, and with normal conventional PTA (125 Hz–8 kHz) were enrolled in the tinnitus group. Volunteers without tinnitus of the same age were enrolled in the control group.

**Main Outcome Measures:** The incidence of EHF-HL and the hearing thresholds at each frequency, as well as the distribution of maximum HL frequency and edge frequency in all participants were compared.

**Results:** In total, 28 cases (43 ears) were enrolled in the tinnitus group and 34 cases (68 ears) in the control group. The incidence of EHF-HL, average hearing threshold of each frequency ranging from 4 to 16 kHz, and the maximum hearing threshold were significantly higher in the tinnitus group. The edge frequency in the tinnitus group was lower than that in the control group (10.4 ± 3.1 kHz versus 12.3 ± 2.5 kHz, p = 0.010). The dominant tinnitus pitch in cases whose EHF was impaired was positively correlated with the hearing-level loudness of tinnitus (r = 0.627, p < 0.001).

**Conclusion:** Patients with tinnitus and normal hearing in conventional PTA showed signs of EHF-HL and hidden damage in the high-frequencies more easily. EHF hearing tests and the follow-up of HF hearing tests are recommended to facilitate early detection of hearing impairment for timely intervention.

**Key Words:** Edge frequency—Extended high-frequency hearing loss—Pure-tone audiometry—Tinnitus.

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Tinnitus is a symptom of auditory perception in the absence of external acoustic or electric stimuli. Patients with tinnitus often describe various sounds appreciated by them as buzzing, ringing, or mixed noises. McCormack et al. (1) reviewed many adult studies reporting the prevalence of tinnitus from January 1980 to July 2015. According to these reports, the overall prevalence of tinnitus (with or without hearing impairment) worldwide was 5.1 to 42.7% during that period, and it increased with age and noise exposure. Hearing loss (HL) is a common and important risk factor for patients with tinnitus (2–4), who generally exhibit increase in hearing thresholds in conventional pure-tone audiometry (PTA), especially in the high-frequency range (5–7). Additionally, 20% patients with tinnitus (8) do not have any detectable HL in the frequency of conventional PTA (125 Hz–8 kHz) (9), or their hearing thresholds do not reach the standard for hearing impairment. Despite these findings, other studies have found that tinnitus patients with
normal audiograms show a significant decrease in the amplitude of the I-wave potential in the auditory brainstem response (ABR) (9), indicating that the synapses between hair cells and/or auditory nerve fibers become damaged, which could be related to the occurrence of tinnitus.

Some studies have suggested the possibility of “hidden hearing loss” in tinnitus patients with normal hearing. The human cochlea can sense sounds in the frequencies between 20 Hz and 20 kHz, but conventional PTA cannot detect HL at frequencies above 8 kHz and does not fully, and reliably, reflect the HL of patients with tinnitus (10). Vielsmeier et al. (11) reported that 83% tinnitus patients with normal hearing had elevated hearing thresholds (>15 dB HL) at one or more of the following frequencies: 10, 11.2, 12.5, 14, and 16 kHz. Similarly, Kim et al. (5) reported that 74% patients with tinnitus who had normal hearing at 8 kHz experienced thresholds more than 25 dB HL at 12 kHz and/or 16 kHz.

Some studies (12,13) have reported the possibility of increased extended high-frequency hearing loss (EHF-HL) in patients with normal hearing and tinnitus. It has been found that an increasing number of young patients with tinnitus have normal conventional PTA results. Nevertheless, until now it is still uncertain whether they have hearing abnormalities in the EHF area compared with their peers without tinnitus, and if the audiological characteristics of tinnitus match the anatomical areas of damage.

In this study, EHF hearing threshold tests, auditory tinnitus tests, and scale evaluation were performed in young patients with tinnitus and normal conventional PTA results, to understand the prevalence and characteristics of EHF-HL. The tendency of this HL to be evident in PTA was analyzed to explore the correlation between tinnitus and EHF-HL. The correlation between the loudness of tinnitus and frequency of HL is the basis for whether EHF audiometry should be recommended as a standard diagnostic procedure for routine evaluation of patients with tinnitus (14).

MATERIAL AND METHODS

Ethical Considerations

The study was approved by the Ethics Committee of the participating hospital. All participants understood the purpose of the study, were able to complete the experiment as directed, and signed an informed consent form. The patients’ records and information were anonymized before analysis.

Study Design and Participants

A case–control study design was used to identify outpatients with tinnitus who visited the otology department of the participating hospital from September 2017 to May 2019. The inclusion criteria for patients with tinnitus were: 1) 18 to 35 years old; 2) subjective tinnitus; 3) duration of tinnitus more than or equal to 3 months; 4) no abnormal findings in conventional PTA (hearing threshold ≤25 dB at any frequency between 125 Hz and 8 kHz).

Exclusion criteria comprised: 1) vascular pulsating tinnitus or objective tinnitus; 2) significant air-bone gap in PTA; 3) obvious health problems that could affect the results; 4) identified as unsuitable by the researchers (unable to cooperate with the data collection process; any other substantiated subjective reason). The cases in the control group were volunteers with normal hearing and without tinnitus. The inclusion criteria for them were: 1) 18 to 35 years old; 2) no tinnitus and HL; 3) volunteered for routine and EHF hearing tests. The exclusion criteria for the controls were: 1) conventional PTA revealing hearing impairment (>25 dB at any frequency between 125 Hz and 8 kHz); 2) obvious health problems that could affect the results; 3) identified as unsuitable by the researchers (unable to cooperate with the data collection process; any other substantiated subjective reason).

Clinical Variables Collection

Demographic information, PTA data collection, and EHF audiometry tests were performed in all enrolled participants. Conventional PTA analyses included the following frequencies: 125, 250, 500 Hz, 1, 2, 4, and 8 kHz. EHF audiometry included the frequencies: 10, 12.5, 14, 16, 18, and 20 kHz. Hearing thresholds were determined using the standard Hughson–Westlake program (step: 10 dB down, 5 dB up; two out of three). The results of audiology tests were collected, and the average hearing threshold of the two groups was calculated. Hearing threshold more than 25 dB at any frequency between 10 and 20 kHz was defined as EHF-HL. The number and proportion of ears with EHF-HL were counted thereafter. The maximum hearing threshold was compared, and the maximum HL frequency and the HL edge frequency were calculated. The formula used for calculating edge frequency was: \( L(f_2) - L(f_1)/\log_{10}(f_2/f_1) \) (6). By calculating the slope of HL, the frequency at which the maximum slope occurred was considered as the edge frequency. If same result was obtained after calculation at several frequencies, then the lowest frequency was selected as the maximum HL frequency or the edge frequency \( (6,15,16) \). Tinnitus-related examinations included dominant tinnitus pitch (125, 250, 500 Hz, 1, 2, 4, 8, and 10 kHz) and loudness matching (sensation-level and hearing-level). The loudness of hearing-level is the actual value of sound intensity output by the audiometer, while the loudness of sensation-level is equal to the loudness of hearing-level minus the hearing threshold at the tinnitus frequency. Audiometry and tinnitus matching were performed using an audiometer (Madsen Aestera; GN Otometrics, Germany) with headphones (HDA-300 over the ear; Sennheiser electronic GmbH & Co. KG, Germany). The Tinnitus Handicap Inventory (THI) was performed on patients with tinnitus.

Statistics

Continuous distribution variables were expressed as mean ± standard deviation. The normally distributed variables of the groups were compared using the independent sample \( t \) test, and the non-normally distributed variables of the groups were compared using the...
nonparametric equivalent (Mann–Whitney U test). Categorical variables were expressed in terms of frequency (percentage) and compared using the $\chi^2$ test and Fisher’s exact test. The Spearman’s correlation test was used to detect the relation between dominant tinnitus pitch and frequency of HL. $p < 0.05$ was considered statistically significant using two-tailed tests.

RESULTS

Demographic Data

A total of 169 patients with tinnitus and 40 healthy volunteers without tinnitus were enrolled in the screening process. Following the application of the inclusion and exclusion criteria, the number of participants included in the tinnitus group was 28 and the control group was 34 (Fig. 1). The average duration of tinnitus in the tinnitus group was $17.9 \pm 17.1$ months, and the average THI score was $37.4 \pm 20.5$. There were no significant differences in age ($28.0 \pm 4.7$ yrs versus $29.1 \pm 3.4$ yrs, $p = 0.206$) and sex (men $46.4\%$ versus $47.8\%$, $p = 0.961$) distribution between the tinnitus and control groups. In the tinnitus group, 13 participants had unilateral tinnitus, and 15 had bilateral tinnitus, resulting in a total of 43 ears that were assessed (21 right ears; 22 left ears). The total number of ears in the control group was 68 (34 right ears; 34 left ears).

Hearing Threshold Comparison

The average hearing threshold at each frequency was compared between the two groups. The results showed that the incidence of EHF-HL in the tinnitus group was 72.1%, which was significantly higher than the 42.6% incidence in the control group ($p = 0.003$). The mean hearing threshold of the tinnitus group in the EHF range was significantly higher than that of the control group (19.7 $\pm$ 7.9 dB versus 12.0 $\pm$ 8.2 dB, $p < 0.001$). There was a statistically significant difference between the tinnitus and control groups in terms of the threshold of maximum HL, and the distribution of edge frequency, while no significant difference in the frequency of maximum HL was observed (Table 1, Fig. 2).

After comparing the hearing thresholds at each frequency in the two groups, we found that the tinnitus group had significantly higher average hearing thresholds at seven frequency points (4, 6, 8, 10, 12.5, 14, and 16 kHz) compared with the control group (Table 2, Fig. 3). Although the thresholds of the tinnitus group were normal in conventional PTA ($\leq$8 kHz), the mean hearing thresholds at 4, 6, and 8 kHz frequencies were higher than those in the control group. Moreover, the standard deviations were quite large in relation to the mean values in both groups, which means that there is a big variability of the hearing threshold value at each frequency point in young people.

| Characteristics of Audiogram | Tinnitus Group | Control Group | $p$ Value |
|-------------------------------|----------------|---------------|-----------|
| Number of ears (incidence) of EHF-HL | 31 (72.1%) | 29 (42.6%) | 0.003 |
| Average EHF hearing threshold (dB, mean $\pm$ SD) | 19.7 $\pm$ 7.9 | 12.0 $\pm$ 8.2 | $<0.001$ |
| Hearing threshold of maximum HL (dB, mean $\pm$ SD) | 48.7 $\pm$ 10.6 | 43.8 $\pm$ 8.1 | 0.048 |
| Dominant tinnitus pitch (kHz) | 7.6 $\pm$ 1.2 | / | / |
| Frequency of maximum HL (kHz) | 14.8 $\pm$ 1.8 | 15.6 $\pm$ 1.4 | 0.064 |
| Edge frequency of HL (kHz) | 10.4 $\pm$ 3.1 | 12.3 $\pm$ 2.5 | 0.010 |

*EHF, extended-high frequency.
*HL, hearing loss.
*SD, standard deviation.

FIG. 1. The flow chart of the study. PTA indicates pure-tone audiometry.
The Correlation Between Dominant Tinnitus Pitch and Each Audiological Parameter

We analyzed the dominant tinnitus pitch in 29 ears with EHF injury in the tinnitus group. The Spearman’s correlation analyses were performed for analyzing the relations among dominant tinnitus pitch, maximum HL frequency, edge frequency, maximum hearing threshold, and loudness (both sensation-level and hearing-level). The results showed that the dominant tinnitus pitch of the EHF-injured ears was not correlated with maximum HL frequency, edge frequency, or sensation-level loudness, but was positively correlated with hearing-level loudness ($r = 0.627$, $p < 0.001$). The maximum hearing threshold showed a weak negative correlation with maximum HL frequency ($r = -0.361; p < 0.01$), and this relationship was stronger when the volunteers with EHF injury in the control group were included ($r = -0.470, p < 0.01$).

THI Scale Results in the Tinnitus Group

There were no significant differences in THI scores between patients with EHF injury ($n = 21$) and those with normal EHF results ($n = 7$) (40.0 ± 22.9 versus 30.0 ± 12.8; $p = 0.209$).

DISCUSSION

Clinically, many patients with tinnitus have normal conventional PTA results, but their hearing thresholds in the EHF range could be higher than the normal value. Our research confirms this finding in young patients, as in this study, 72.1% patients with tinnitus and normal response on PTA had different degrees of EHF-HL, which was statistically different from the control group patients without tinnitus. The results also showed that the hearing thresholds at each point from 4 to 16 kHz in the tinnitus group were significantly higher than those in the control group. Interestingly, although the hearing thresholds from 4 to 8 kHz in the tinnitus group were still within the normal range, these were significantly higher compared with that in the control group. Therefore, in patients with tinnitus and normal PTA, not only the possibility of EHF-HL but also of HL in the high-frequency region of conventional PTA examination exists.

Our study found that the young population, with age ranging from 18 to 35 years, exhibiting normal PTA but EHF injury, had a mean maximum HL frequency of 14.8 ± 1.8 kHz and an edge frequency of 10.4 ± 3.1 kHz. Overall, the tinnitus group had higher values than the control group (15.6 ± 1.4 and 12.3 ± 2.5 kHz). Although the difference in maximum HL frequency between the two groups showed a weak negative correlation with maximum HL frequency ($r = -0.361; p < 0.01$), and this relationship was stronger when the volunteers with EHF injury in the control group were included ($r = -0.470, p < 0.01$).

**TABLE 2.** Comparison of the hearing thresholds between the control group and tinnitus group at each frequency

| Frequency | Tinnitus Group (dB, Mean ± SD) | Control Group (dB, Mean ± SD) | p Value |
|-----------|--------------------------------|------------------------------|---------|
| 125 Hz    | 0.5 ± 3.4                      | 0.7 ± 1.8                    | 0.621   |
| 250 Hz    | 0.5 ± 3.5                      | 1.0 ± 2.2                    | 0.346   |
| 500 Hz    | 0.8 ± 3.9                      | 0.9 ± 2.4                    | 0.903   |
| 1 kHz     | 1.4 ± 5.4                      | 1.0 ± 2.7                    | 0.651   |
| 2 kHz     | 2.7 ± 5.6                      | 1.8 ± 3.8                    | 0.290   |
| 3 kHz     | 3.9 ± 6.3                      | 2.7 ± 3.9                    | 0.227   |
| 4 kHz     | 3.4 ± 5.4                      | 1.3 ± 2.9                    | 0.010   |
| 6 kHz     | 5.2 ± 7.7                      | 2.7 ± 5.0                    | 0.038   |
| 8 kHz     | 6.0 ± 8.5                      | 3.1 ± 5.6                    | 0.029   |
| 10 kHz    | 15.2 ± 16.3                    | 6.3 ± 9.1                    | <0.001  |
| 12.5 kHz  | 21.9 ± 21.5                    | 9.3 ± 11.1                   | <0.001  |
| 14 kHz    | 27.2 ± 22.0                    | 13.4 ± 15.6                  | <0.001  |
| 16 kHz    | 34.2 ± 19.4                    | 25.4 ± 17.5                  | 0.023   |
| 18 kHz    | 19.1 ± 7.9                     | 16.8 ± 6.4                   | 0.166   |
| 20 kHz    | 0.8 ± 3.4                      | 0.7 ± 2.7                    | 0.820   |

aSD, standard deviation.
was not statistically significant, the $p$-value was 0.064, which approached statistical significance; thus, the differences between the two groups should be analyzed in further large-scale studies to validate the results of our study. The difference in edge frequency between the two groups was statistically significant ($p = 0.010$). This result suggests that tinnitus is not only related to the elevated EHF hearing thresholds but also extends the damaged frequency range to a lower frequency region, as shown by the movement of the hearing curve simultaneously downward and toward the left.

The relationship between dominant frequency matching and frequency of HL (maximum HL frequency and edge frequency) has always been the entry point for the academic community to elaborate the hypothesis of the respective tinnitus occurrence mechanism. The tonotopic reorganization model suggests that HL results in reorganization of the disturbed tonotopic map in the primary auditory cortex, whereby neurons with characteristic frequencies within the deprived region adopt the tuning properties of their less-affected neighbors (17). Conversely, the neural synchrony model hypothesizes that tinnitus is generated by increased neuronal synchronization in the HL region (18,19), implying that the dominant tinnitus pitch generally falls in the area of hearing impairment (20–22) and corresponds to the frequency of maximum HL (23,24). The boundary frequency between the normal hearing and HL zones is called the “edge frequency,” and some studies have shown that it is correlated with the dominant tinnitus pitch of patients with tinnitus (6,15,16). König et al. (6) found a weak, but significant, relationship between dominant tinnitus pitch and audiometric edge frequency, while Moore et al. (16) claimed that a stronger and more significant correspondence existed between the dominant tinnitus pitch and low-edge frequency after octave error training.

Our study found that dominant tinnitus pitch was not related to the maximum HL frequency and edge frequency, which is in contrast to the results of previous studies. The reason for the difference could be studies that confirmed this correlation mainly included patients with tinnitus and hearing impairment in conventional PTA examination. The frequency at which the dominant tinnitus pitch was matched was also within the frequency range of conventional PTA. Our study was performed on patients with tinnitus and normal PTA, whose frequency of hearing impairment was in the EHF region.

The hearing-level loudness matching was calculated by sensation-level loudness matching plus the fine hearing threshold at the corresponding frequency. Our results showed a positive correlation between the dominant tinnitus pitch and hearing-level loudness ($r = 0.627; p < 0.001$) of tinnitus, but no correlation with the sensation-level loudness, indicating that the dominant tinnitus pitch is related to the fine hearing threshold of the frequency. In general, the hearing thresholds of the ears increase with the increasing frequency of the test sounds. Therefore, the fine listening thresholds of high-frequency tinnitus are generally higher than that of low-frequency tinnitus, resulting in a positive correlation between the dominant tinnitus pitch and hearing-level loudness. Interestingly, the maximum hearing threshold showed a weak negative correlation with maximum HL frequency ($r = -0.361; p < 0.01$), and this result was more pronounced when the number of participants in the control group included those with the EHF injury ($r = -0.470; p < 0.01$). This suggests that more the obvious damage in hearing threshold, greater the tendency for the maximum HL frequency to move to the lower frequency region, until the PTA detection region is eventually involved. Higher the maximum HL frequency, smaller the maximum hearing threshold of the patient, resulting in a greater tendency for normal hearing. Therefore, it

![FIG. 3. The comparison of the mean hearing thresholds at each frequency between the tinnitus and control groups (error bars denote 1 standard deviation).](image-url)
can be speculated that tinnitus patients with normal hearing in PTA are likely to have HL in the EHF region. If this is not identified and the factors that might cause hearing impairment over time are not appropriately addressed, hearing in the routine audiogram could be gradually involved, which could lead to the aggravation of tinnitus. It is known that tinnitus, especially worsening tinnitus can affect sleep and even lead to anxiety, depression, and suicide.

Our results showed that most young patients with tinnitus and normal hearing in conventional PTA had HL in the EHF region and exhibited potential damage performance in the high-frequency area. In addition to regular hearing protection advices such as avoiding noise exposure and limiting the use of ototoxic medicines, EHF tests should be recommended in such patients. An individualized tinnitus treatment program such as sound therapy according to the results of EHF test, including frequency, degree of maximum HL, edge frequency, and tinnitus pitch matching, should be designed. At the same time, the treatment efficiency could be determined by monitoring the changes in HL in the EHF area.

In the tinnitus group, there was no significant difference in the THI score between patients with EHF injury and those without, indicating that EHF injury does not affect the degree of tinnitus annoyance.

There are several limitations in the study. First, only tinnitus patients with normal PTA younger than 35 years of age were enrolled in this study to avoid the effect of aging on HL. However, this limited the sample size of the study. Second, the upper limit of the dominant tinnitus pitch was 10 kHz, which is considerably lower than the frequency (20 kHz) achieved in EHF hearing tests. Hence, the tinnitus pitch matching in the EHF region could not be performed precisely. Third, as a case-control study, there is a lack of evidence pertaining to the sequence and interaction of tinnitus and EHF-HL. Future studies should incorporate prospective, long-term follow-up assessments to confirm and substantiate such relationships.

**CONCLUSION**

Young patients with tinnitus and normal hearing in conventional PTA showed higher rates of EHF (10–20 kHz) HL and higher EHF thresholds than those without tinnitus. Moreover, hidden damage presenting as threshold increase in the high frequencies (4–8 kHz) was also observed in these patients, even if their hearing thresholds were in the normal range (≤25 dB) in PTA. Therefore, EHF hearing tests and follow-up high-frequency hearing threshold tests should be recommended to facilitate early detection of hearing impairment for timely intervention. We wish that further definite evidence could be provided to ascertain the relation between EHF-HL and the risk of HL progression to the conventional frequencies in the long term. Further research on the sequence and interaction of tinnitus and EHF-HL is warranted.

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