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Research Paper

Extended High Frequency Hearing Thresholds in Tinnitus Patients with Normal Hearing

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The aim of the study was to compare the extended high-frequency (EHF) hearing thresholds (10–16 kHz) in tinnitus and non-tinnitus ears, in a group of 98 patients with unilateral tinnitus and normal hearing at standard audiometric frequencies, in a 0.125–8 kHz range. It was found that a total of 65 patients (66%) had a hearing loss (a threshold shift >20 dB HL) in the EHF range and the EHF hearing loss occurred more frequently in the tinnitus ear than in the non-tinnitus ear. The data also indicate that the EHF thresholds increased with the patient's age and were in most patients higher in the tinnitus ear than in the non-tinnitus ear.

Keywords: extended high frequency; hearing loss; tinnitus.

1. Introduction

Tinnitus is defined as sound perception in the absence of a sound source (Azevedo *et al.*, 2020). The estimated prevalence of tinnitus among adults is 14.7%, 14% in men and 15.2% in women (BISWAS *et al.*, 2022). The most common classification categorizes tinnitus as objective or subjective, according to whether the sound is heard only by the patient or also by the examiner. Tinnitus patients hear tonal ringing, buzzing, clicking, hissing, and other noises (WANG *et al.*, 2020). The pitch of tinnitus usually falls within the patient's hearing loss frequency range (RISTOVSKA *et al.*, 2019; KEPPLER *et al.*, 2017). There is a variety of risk factors for developing tinnitus with hearing loss being the main factor. Otological risk factors include: sensorineural hearing loss, noise exposure, presbyacusis, otosclerosis, impacted cerumen, otitis media, Ménière's disease, labyrinthitis, mastoiditis, vestibular schwanoma, etc. There are also neurological risk factors: traumatic, orofacial, cardiovascular, rheumatological, immune-mediated, endocrine, and metabolic factors, psychological risk factors, and risks posed by ototoxic medications (BAGULEY *et al.*, 2013). Tinnitus is thought to result from abnormal neural activity at some point or points in the auditory pathway which is erroneously interpreted as sound by the brain (HOARE *et al.*, 2014). No single theory explaining the cause of tinnitus has been universally accepted (MCCORMACK *et al.*, 2014). According to one theory tinnitus is likely to be induced by a discontinuity in the spontaneous or low-level stimulus induced neural activity across auditory nerve fibers with different characteristic frequencies. Such a reduced spontaneous activity of nerve fibers with characteristic frequencies corresponding to the hearing loss range may result in a reduction of lateral inhibition at more central levels. In turn, the reduced lateral inhibition of neurons with characteristic frequencies close to the edge frequency of the patient's hearing range causes hypersensitivity and hyperactivity in those neurons (EGGERMONT, 2003). Although central mechanisms are important for an explanation of the tinnitus-related activity, many of these mechanisms appear to be triggered by a reduction of cochlear activity. However, a damage to cochlear tissues is not always necessary to produce tinnitus as tinnitus may also be caused by a conductive hearing loss (Haider *et al.*, 2018).

Most cases of tinnitus are associated with a hearing loss which may be either apparent in an audiogram or detected by more sensitive measures (Roberts *et al.*, 2013). Chronic tinnitus is most often associated with hearing loss induced by noise exposure or results from the aging process (Eggermont, Roberts, 2004). Folmer (2002) reported that approximately 90% of tinnitus patients who were examined in his study had some degree of hearing loss. Nicolas-Puel *et al.* (2002) also found associated hearing loss of known ethology in almost 90% of tinnitus patients. A more recent study has shown that 91.9% of tinnitus patients had hearing loss at conventional audiometric test frequencies, 125–8000 Hz (Ristovska *et al.*, 2016). In tinnitus patients with normal hearing in conventional audiometry tinnitus may be explained by an extended high frequency (EHF) hearing loss (Rodriguez Valiente *et al.*, 2016). Mujdeci and Dere (2019) found higher EHF hearing thresholds in tinnitus ears than in non-tinnitus ears. Kim *et al.* (2011) reported hearing impairment in the EHF range in 74% of tinnitus patients who had no hearing impairment at conventional audiometry frequencies. These results support the deafferentation hypothesis which postulates that cochlear damage is a major factor triggering tinnitus, also in patients with normal conventional audiograms. Recently, there has been much interest in EHF thresholds in studies of cochlear synaptopathy caused by ageing and noise exposure, as well as in EHF thresholds measured in patients treated with ototoxic drugs (Prendergast *et al.*, 2020). The published results indicate that there are alterations in the affected side of the auditory system in patients with unilateral tinnitus and normal hearing sensitivity in the conventional audiometry frequency range, manifested as elevated EHF thresholds. In addition, the distortion product otoacoustic emission (DPOAE) levels are lower in tinnitus ears than in non-tinnitus subjects (Fabijańska *et al.*, 2019). Song *et al.* (2021) reported higher EHF (10–20 kHz) hearing loss rates in young patients with tinnitus and normal hearing in conventional audiometry, as well as higher EHF thresholds, than in patients with no tinnitus. They recommended EHF audiometric testing to facilitate early detection of hearing impairment and ensure timely medical treatment. In an earlier study, Sanches *et al.* (2010) concluded that EHF audiometry and DPOAE measurements may identify early damage to the cochlea that is not detectable by conventional audiometry in tinnitus patients. According to Liberman *et al.* (2016) EXF audiometry is a useful method for the detection of hidden hearing loss, especially in young people exposed to hazardous noise levels, who have normal conventional audiograms.

Clinical audiometry, the gold standard for detecting hearing loss, typically measures hearing thresholds within a frequency range extending up to 8 kHz but a healthy young person can usually hear pure tones up to about 20 kHz (Hunter *et al.*, 2020). The EHF thresholds were studied in different age groups in order to obtain reference thresholds for international audiometric standards (Rodriguez Valiente *et al.*, 2014). The reference equivalent threshold sound pressure levels (RETSPLs) have been specified in the ISO 389-5 standard for frequencies from 8 to 16 kHz. The RETSPL determines the 0 dB reference hearing level (0 dB HL) in audiometry. EHF audiometry may be used for the hearing threshold measurement at frequencies spaced at 1/6-octave intervals: 9, 10, 11.2, 12.5, 14, and 16 kHz (Jilek *et al.*, 2014).

In this study EHF thresholds were evaluated in patients with unilateral tinnitus and normal hearing at standard audiometric frequencies and compared to the EHF thresholds in tinnitus ears and non-tinnitus ears. The objective of the study was to test an assumption that the majority of tinnitus patients with normal hearing at conventional audiometric test frequencies have EHF hearing loss and the EHF thresholds are higher in tinnitus ears than in non-tinnitus ears.

2. Patients and methods

The study included a sample of 98 patients with unilateral tinnitus, 52 males (53.1%) and 46 females (46.9%), aged 18 to 58 years (mean age of 36.2 ± 10.8 years), and was a retrospective review of data collected at the Department of Otorhinolaryngology, Division of Audiology, City General Hospital "8th September", Skopje, during the period from January 2017 to June 2021. The inclusion criteria were: subjective unilateral tinnitus, normal hearing at conventional audiometric test frequencies, and normal middle-ear function with type A tympanograms. Pure tone audiometry and tinnitus psychoacoustic assessment were performed in a sound-proof booth with the use of a GN Otometrics MADSEN Astera^2 audiometer and Sennheiser HDA 300 circumaural headphones. Similarly as in (Poling *et al.*, 2016), the hearing thresholds were measured using a modified Hughson-Westlake manual method at standard frequencies within a 125–8000 Hz range, and EHF frequencies: 10000, 12500, 14000, and 16000 Hz. Normal hearing was defined as a threshold value of 20 dB HL or less at frequencies from 125 to 8000 Hz. The EHF hearing loss was defined as a threshold value exceeding 20 dB HL at frequencies from 10000 to 16000 Hz. We did not calculate EHF pure tone average (PTA) as the EHF thresholds were analysed separately for each frequency. Statistical analysis of the data was performed using the Chi-square test, the Mann-Whitney U test and the Pearson correlation coefficient, with a significance level of $p < 0.05$. The Protocol number of ethical approval is 1360-1/2021.

3. Results

The mean age of patients with normal EHF hearing and those with EHF hearing loss was, respectively, 29.3 ± 8.3 years and 39.7 ± 10.2 years. The distribution of the patients in terms of tinnitus laterality and the presence of hearing loss at extended high frequencies in tinnitus ears is shown in Table 1.

The cases of EHF hearing loss in the tinnitus ear and in the contralateral non-tinnitus ear are displayed in Table 2. The data show that EHF hearing loss was more common in tinnitus ears and that there was a statistically significant difference between the presence of tinnitus and the presence of EHF hearing loss ($\chi^2 = 18.375$, $df = 1$, $p < 0.001$).

Table 3 is a comparison of EHF thresholds in tinnitus and non-tinnitus ears. The data are the median thresholds at each of the EHF test frequencies. A statistical analysis with a Mann-Whitney U test has shown significantly higher hearing thresholds in tinnitus ears than in non-tinnitus ears at all frequencies tested ($p < 0.05$).

In a number of cases the patients did not respond to the test tone at the maximum output level. This level was set by the manufacturer of the audiometer as follows: 80 dB at 10000 Hz, 70 dB at 12500 Hz, 60 dB at 14000 Hz, and 40 dB at 16000 Hz. In terms of tone frequency, testing was possible up to 16000 Hz.

Figure 1 shows the mean EHF hearing thresholds of tinnitus and non-tinnitus ears and the associated standard deviation error bars.

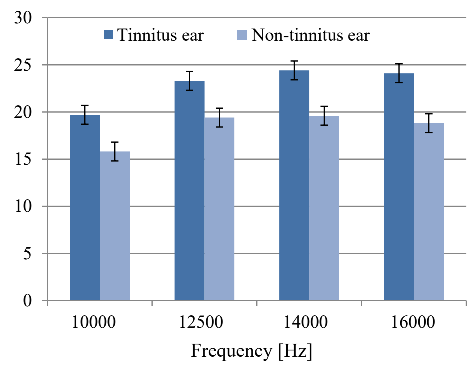

Fig. 1. Mean EHF hearing thresholds in tinnitus and non-tinnitus ears and the standard deviation error bars.

Table 4 shows the age range of tinnitus patients and their threshold ranges at each of the test frequencies. At a frequency of 16000 Hz, the oldest patient who responded to the test tone at the maximum output level was 56 years old. At all the other test frequencies the responses were obtained from all patients, aged up to 58 years. A statistical analysis with Pearson correla-

Table 1. Tinnitus laterality and EHF hearing loss in tinnitus ears.

Tinnitus laterality	Normal EHF hearing		EHF hearing loss		Total	
	Number of patients	[%]	Number of patients	[%]	Number of patients	[%]
Right ear	15	15.3	27	27.6	42	42.9
Left ear	18	18.4	38	38.8	56	57.1
Total	33	33.7	65	66.3	98	100

Table 2. Hearing loss at extended high frequencies in the tinnitus ear and non-tinnitus ear.

Patient's test ear	Normal EHF hearing		EHF hearing loss		Total	
	Number of patients	[%]	Number of patients	[%]	Number of patients	[%]
Tinnitus ear	33	16.8	65	33.2	98	50
Contralateral ear	63	32.1	35	17.9	98	50
Total	96	49	100	51	196	100

Chi-square test ($p < 0.001$).

Table 3. A comparison of EHF thresholds in tinnitus and non-tinnitus ears.

Frequency [Hz]	Tinnitus ears (98 ears)	Non-tinnitus ears (98 ears)	p^*
	Median (min–max)	Median (min–max)	
10000	15 (5–55) n = 98	15 (5-45) n = 98	0.029
12500	20 (5–65) n = 98	15 (5–55) n = 98	0.048
14000	20 (5–60) n = 77	15 (5–60) n = 83	0.019
16000	20 (5–40) n = 67	15 (5–40) n = 73	0.015

* Mann-Whitney U test; n – number of responses, non-responding cases were excluded.

Table 4. Correlation between the patients' age and the EHF hearing thresholds in tinnitus ears.

Frequency [Hz]	Age range	Threshold range	r	p^*
10000	18–58	5–55	0.601	< 0.001
12500	18–58	5–65	0.618	< 0.001
14000	18–58	5–60	0.697	< 0.001
16000	18–56	5–40	0.636	< 0.001

* Pearson correlation coefficient.

Table 5. Tinnitus pitch in patients with normal EHF hearing and EHF hearing loss.

Pitch-match frequency [Hz]	Normal EHF hearing		EHF hearing loss		Total	
	Number of patients	[%]	Number of patients	[%]	Number of patients	[%]
250	2	2	6	6.1	8	8.2
500	2	2	1	1	3	3.1
1000	3	3.1	1	1	3	3.1
2000	4	4.1	2	2	6	6.1
3000	1	1	2	2	3	3.1
4000	10	10.2	10	10.2	20	20.4
6000	2	2	8	8.1	10	10.2
8000	9	9.2	16	16.3	25	25.5
10000	–	0	12	12.2	12	12.2
12500	–	0	7	7.1	7	7.1
Total	33	33.7	65	66.3	98	100

tion coefficient has shown a moderate positive correlation between the patient's age and the EHF hearing threshold at all frequencies.

Tinnitus pitch was determined in all patients (Table 5). In a total of 98 patients only 19 (19.4%) had a tinnitus pitch falling within the area of EHF hearing loss, that is 29.2% of patients with EHF hearing loss. Twelve patients (12.2%) matched their tinnitus pitch to a 10000-Hz tone and seven patients (7.1%) to a 12500-Hz tone, the tone frequencies at which their hearing thresholds were elevated.

A total of 78 patients (79.6%) had a tonal tinnitus and 20 patients (20.4%) a noise-like tinnitus. The tinnitus loudness was determined at the pitch-match frequency in dB SL, as the tone sensation level expressed relative to the hearing threshold. The mean tinnitus loudness in 19 patients (19.4%) who reported a tinnitus pitch corresponding to the hearing loss area was 4.8 ± 2.3 dB SL and the loudness of their tinnitus sensation ranged from 3 to 11 dB SL. The mean tinnitus loudness in 79 patients (80.6%) who matched their tinnitus to a frequency within the range of normal hearing was 7.1 ± 2.5 dB SL and the tinnitus loudness ranged in this subgroup from 3 to 16 dB SL.

4. Discussion

The measurements of EHF thresholds in patients with unilateral tinnitus and normal hearing at conventional audiometric test frequencies have shown that an EHF hearing loss was present in 66.3% of the patients which is a slightly lower percentage than reported by Kim *et al.* (2011). Kim *et al.* (2011) found an EHF hearing loss in 74% of the tinnitus patients who showed no hearing impairment in conventional audiometry. More recently, Song *et al.* (2021) reported an EHF hearing loss in 72.1% young tinnitus patients who had normal hearing in conventional audiometry. In the present study EHF thresholds were significantly higher in tinnitus ears than in non-tinnitus ears. These results are consistent with the findings of Mujdeci and Dere (2019) who compared hearing thresholds at conventional audiometric test frequencies and EHFs, and reported significantly higher thresholds in tinnitus ears, comparing to non-tinnitus ears at 10000, 12500, 14000, and 16000 Hz. It also should be noted that there was a difference between the maximum test tone output levels in their measurements and in the present study as the levels used in the Mujdeci and Dere (2019) study were higher. In the present study, the EHF thresholds of tinnitus patients were not compared with EHF thresholds of age-matched and gender-matched control subjects due to the possibility of a difference between the patients and the control group in their noise exposure history, ototoxic medication treatment, or age related EHF hearing loss.

Several studies have found higher thresholds in the EHF region in normal hearing individuals with tinnitus compared to non-tinnitus control subjects, which implies that cochlear damage in the basal region may result in a perception of tinnitus (Omidvar *et al.*, 2016; Fabijańska *et al.*, 2012; Kim *et al.*, 2011; Yildirim *et al.*, 2010; Shim *et al.*, 2009). In contrary to those findings, a study conducted by Elmoazen *et al.* (2018) did not reveal any significant difference in the mean EHF thresholds between a group of tinnitus patients with normal hearing and a group of age-matched and gender-matched tinnitus-free controls which suggests that the presence of tinnitus in a patient with normal conventional audiogram does not necessarily due to a detectable cochlear damage in the EHF and may reflect a more central cause of tinnitus in the auditory system. A number of patients in our study reported exposure to excessive noise, either in occupational or non-occupational settings, and some patients used ototoxic medications. Our results highlight the importance of EHF testing. EHF audiometry is needed in assessment of tinnitus patients because it can be useful for early detection of sensorineural hearing loss, for example, in cases of noise-induced hearing loss or ototoxicity. Along with the other diagnostic procedures it could help detect "hidden hearing loss".

In terms of laterality, tinnitus was more common in the left ear in our study which is in agreement with the findings of other studies (Steinmetz *et al.*, 2009; Weisz *et al.*, 2005). Vielsmeier *et al.* (2015) found a relationship between tinnitus laterality and hearing asymmetry: patients with left-sided tinnitus also had more pronounced HF-hearing impairment on the left side. According to Baguley *et al.* (2013) tinnitus is more frequently left-sided than right-sided also in patients with hearing loss at conventional audiometric test frequencies. The reason for left-sided preponderance is unknown and cannot be explained by asymmetric hearing loss.

The present study has shown that EHF thresholds increase with the patient's age. A moderate positive correlation between the patient's age and the EHF hearing threshold was observed at all frequencies. Our findings are consistent with the results of previous studies. An analysis of high-frequency thresholds of individuals with normal hearing has shown that hearing thresholds progressively increase with the test tone frequency and the age advancement (Oppitz *et al.*, 2018; Prestes, Gil, 2009; Silva, Feitosa, 2006).

The majority of our patients had high-pitched tinnitus and the most frequent pitch-match frequencies were 8000 Hz and 4000 Hz. In contrast to what was reported in numerous studies in which tinnitus pitch fell into the area of hearing loss in the majority of patients with hearing loss at conventional audiometric frequencies, we found a corresponding tinnitus pitch within the area of EHF hearing loss in 29.2% of the patients with EHF hearing loss. One may presume that the reason why the most frequent tinnitus pitch-match frequency was 8000 Hz was that it was the edge frequency of the audiogram and the hearing loss occurred above 8000 Hz. Moore *et al.* (2010) defined the edge frequency as the boundary between the frequency of normal/near normal hearing and hearing loss. Some theories of the mechanisms of tinnitus generation lead to the prediction that the pitch associated with tonal tinnitus should be related to the edge frequency of the audiogram.

In our study, the mean loudness of tinnitus falling within the patient's normal hearing frequency range was higher than the mean tinnitus loudness in patients whose tinnitus pitch corresponded to the hearing loss range. The patients often described tinnitus as being perceptually very loud but in fact the tinnitus loudness, expressed as the sensation level of an equally-loud tone, was much lower than indicated by the patient's oral description. This discrepancy may be explained by the loudness recruitment effect. Loudness recruitment is associated with cochlear impairment and refers to an abnormal increased rate of growth in perceived loudness as the intensity level of a sound is increased (Joris, 2009). It also should be mentioned that we did not analyse loudness perception of tinnitus measured on a visual analogue scale.

The study has some limitations that should be noted. One of the limitations is the fact that a number of patients did not respond at the maximum output tone level, especially at frequencies of 14000 and 16000 Hz, so we could not calculate the pure tone average (PTA) of EHF thresholds. If only the hearing thresholds at 10000 Hz and 12500 Hz were included in the calculations the PTA would be lower than it actually was. Another limitation is the lack of a comparison between EHF hearing thresholds in tinnitus patients and EHF thresholds of age-matched and gender-matched subjects with no tinnitus, as a control group.

5. Conclusions

The majority of patients with unilateral tinnitus and normal hearing at standard frequencies had EHF hearing loss and the EHF thresholds were higher in the tinnitus ear than in the non-tinnitus ear. Hearing thresholds increased with the patient's age at all test frequencies in the EHF range. The study has shown that EHF audiometry is a useful complementary test for the diagnostics of tinnitus.

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