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Psychoacoustic Characteristics of Tinnitus in Relation to Audiometric Profile

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The aim of the study was to examine the relationship between tinnitus pitch and maximum hearing loss, frequency range of hearing loss, and the edge frequency of the audiogram, as well as, to analyze tinnitus loudness at tinnitus frequency and normal hearing frequency.

The study included 212 patients, aged between 21 to 75 years (mean age of 54.4 ± 13.5 years) with chronic subjective tinnitus and sensorineural hearing loss. For the statistical data analysis we used Chi-square test and Fisher's exact test with level of significance $p < 0.05$.

Tinnitus pitch corresponding to the frequency range of hearing loss, maximum hearing loss and the edge frequency was found in 70.8%, 37.3%, and 16.5% of the patients, respectively. The majority of patients had tinnitus pitch from 3000 to 8000 Hz corresponding to the range of hearing loss ($p < 0.001$). The mean tinnitus pitch was 3545 Hz $\pm$ 2482. The majority (66%) of patients had tinnitus loudness 4–7 dB SL. The mean sensation level at tinnitus frequency was 4.9 dB SL $\pm$ 1.9, and 13 dB SL $\pm$ 2.9 at normal hearing frequency.

Tinnitus pitch corresponded to the frequency range of hearing loss in majority of patients. There was no relationship between tinnitus pitch and the edge frequency of the audiogram. Loudness matching outside the tinnitus frequency showed higher sensation level than loudness matching at tinnitus frequency.

Keywords: Tinnitus pitch; tinnitus loudness; audiogram; edge frequency; hearing loss.

1. Introduction

Tinnitus is described as the perception of sound without any external stimulation (Wrzosek *et al.*, 2016). It can be categorized as objective or subjective (Bauer, 2018). Tinnitus is thought to result from abnormal neural activity at some point or points in the auditory pathway which is erroneously interpreted by the brain as sound (Hoare *et al.*, 2014). It is referred to as persistent tinnitus when lasting six months or longer (Tunkel *et al.*, 2014). Most cases of tinnitus are associated with hearing loss expressed either in the audiogram or putatively detected by more sensitive measures (Roberts *et al.*, 2013).

The quantification of tinnitus is important for several reasons: to reassure the patients that the symptom is real, to provide information that might help clinician identify the site of origin of tinnitus in the auditory system, to monitor changes in tinnitus, and to assist in legal issues (Nageris *et al.*, 2010).

Psychoacoustic tinnitus assessment includes pitch matching, loudness matching, masking, and residual inhibition (Sanchez, Switalski, 2015). Evidence of systematic relationships between the perceptual characteristics of tinnitus, such as pitch and loudness, and those of the absolute hearing threshold curves, like the presence and degree of hearing loss at certain frequencies, would probably help to understand how tinnitus is related to the configuration of the hearing loss (Norena *et al.*, 2002).

A psychoacoustic assessment of tinnitus frequency can be used to evaluate the neurophysiological mechanisms of tinnitus perception (Keppler *et al.*, 2017). Some theories of 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, the frequency at which hearing loss worsens relatively abruptly (Moore *et al.*, 2010). The tonotopic reorganization model postulates a dominant tinnitus pitch corresponding to the edge frequency due to an over-representation of neurons tuned to frequencies at that audiometric edge (Eggermont, Roberts, 2004). When there is a hearing loss in a certain frequency region, that may result in a loss of inhibition from neurons tuned to that region, this release from inhibition may in turn lead to increased neural activity in an adjacent region tuned to frequencies where there is less hearing loss, giving rise to tinnitus corresponding to the edge frequency (Moore *et al.*, 2010).

Sereda *et al.* (2015) confirmed the previous findings that tinnitus pitch generally falls within the area of hearing loss and the strongest predictor of tinnitus pitch is the degree of hearing loss. In their opinion, these findings are consistent with a homeostatic plasticity view of tinnitus. According to Schaette and Kempter (2006), cochlear damage decreases the mean activity level in a large fraction of neurons in the cochlear nucleus. Decreased mean activity could then trigger homeostatic plasticity, leading to increased spontaneous firing rates (hyperactivity) in the auditory brainstem, which may be perceived as tinnitus.

The aim of this study was to examine the relationship between psychoacoustic characteristics of tinnitus and audiometric profile. We studied the relationship between tinnitus pitch and maximum hearing loss, frequency range of hearing loss, and the edge frequency of the audiogram. We also analyzed tinnitus loudness at tinnitus frequency and normal hearing frequency (1000 Hz).

2. Patients and methods

This retrospective study included a sample of 212 patients, 124 males (58.5%) and 88 females (41.5%), aged between 21 to 75 years (mean ± SD: 54.4 ± 13.5 years), examined at the Department of Otorhinolaryngology, Division of Audiology, City General Hospital "8th September", Skopje, Republic of Macedonia. Ear, nose and throat examination, tympanometry, pure-tone audiometry and tinnitus psychoacoustic assessment were done during the period of January 2017 to July 2018. Inclusion criteria were chronic subjective tinnitus (≥ 6 months), sensorineural hearing loss, normal otoscopic findings, and normal middle-ear function with type A tympanograms. There were different causes of hearing loss. A total of 38 patients (17.9%) reported exposure to gunfire noise in occupational or non-occupational settings. Five patients (2.4%) had idiopathic sudden sensorineural hearing loss. A total of 87 (41%) patients had age-related hearing loss, and 22 of them had coexisting noise-induced hearing loss.

Pure tone audiometry, as well as tinnitus psychoacoustic assessment were performed with MADSEN Astera^2 audiometer (GN Otometrics, Denmark) and HDA 300 circum-aural headphones in sound proof booth. Hearing threshold was determined with modified Hughson-Westlake method for the following frequencies: 125, 250, 500, 750, 1000, 1500, 2000, 3000, 4000, 6000, and 8000 Hz. Normal hearing was defined as thresholds ≤ 20 dB hearing level (HL) at audiometric frequencies from 250 to 8000 Hz. Tympanometry was performed with Amplaid A756 Screening tympanometer (Amplifon, Italy). For the statistical data analysis we used Chi-square test and Fisher's exact test with level of significance $p < 0.05$. The Protocol number of Ethical approval is: 3297/2018.

2.1. Definition of the edge frequency

The edge frequency was defined as in the study conducted by Moore *et al.* (2010). The steps are described in the Table 1.

2.2. Definition of audiogram configuration

Audiogram configuration (shape of the audiometric curves) was defined similar to Pan *et al.* (2009), except the notch configuration. It was defined similar to Pawlaczyk-Luszczyńska *et al.* (2017). The audiograms were classified according to several criteria (Table 2).

Table 1. Definition of the edge frequency.

1	The audiometric thresholds for the frequencies 125, 250, 500, 750, 1000, 1500, 2000, 3000, 4000, 6000, and 8000 Hz were labeled f_1, f_2, f_3, ..., f_{11}
2	The differences in threshold between successive audiometric frequencies (f_2–f_1, f_3–f_2, f_4–f_3, ..., f_{11}–f_{10}) were calculated. These are denoted Δn ($n = 1, ..., 10$)
3	When one value of Δn was larger than all other values of Δn, the edge frequency was taken as corresponding to the lower of the two frequencies for which Δn was largest
4	If there were two equal largest values of Δn, and these two were adjacent to one another in frequency, then the lower one was used
5	The edge frequency defined in this way is denoted f_e

Table 2. Definition of audiogram configuration.

Flat	The difference between the maximum hearing threshold and minimum hearing threshold is less than 25 dB HL
Gradual slope	The difference between maximum hearing threshold and minimum hearing threshold is less than 50 dB
Steep slope	The difference between maximum hearing threshold and minimum hearing threshold is equal to or greater than 50 dB
Inverted "U" shape	Hearing thresholds at 1000 Hz and/or 2000 Hz is 20 dB lower than hearing at 500 Hz and at 4000 Hz
Notch	A sharp drop in the hearing sensitivity at 4000 or 6000 Hz of at least 15 dB in relation to both best preceding threshold occurring at frequencies from 1000 to 3000 (4000) Hz and the threshold at 8000 Hz

2.3. Psychoacoustic assessment of tinnitus

The test ear was the ear where the tinnitus was heard or the ear where predominant or louder tinnitus was present if the tinnitus was bilateral. If the tinnitus was equally loud on both sides, the better hearing ear was selected.

To determine the pitch of the tinnitus a two-alternative forced-choice (2-AFC) method was used. Pitch matching included frequencies from 125 to 8000 Hz with 1/2 octave steps. Pitch matching procedure was performed at most comfortable levels according to previously obtained audiometry results. The testing was ipsilateral with continuous stimulation. A stimulus was pure tone or narrow band noise (NBN). For each of the audiometric test frequencies there is a corresponding band of noise (one-third octave wide) centered around the test frequency. The results were confirmed with an Octave Confusion Test (OCT). Octave confusion refers to the difficulty in distinguishing frequencies 1 octave apart from each other, and judging them as being identical.

The 2-AFC method was also used for loudness matching. The intensity levels were in 1 dB step sizes. The test frequency was the same as the pitch previously reported. In some patients the loudness matching was additionally performed at the frequency of 1000 Hz. Loudness matching is expressed in dB SL (Sensation Level, i.e. dB above hearing threshold).

For examining the maskability, the Masking Noise Threshold was determined by applying NBN ipsilaterally to the affected ear. Starting from −10 dB HL, the noise level was gradually increased until its presence was just detected. Masking Noise Threshold was starting point for determining the Minimum Masking Level (MML). MML was determined by using the ascending method with presentation of masking stimulus in 1 dB HL steps for 1–2 seconds and asking the patient if the noise can mask the tinnitus. MML was recorded in dB HL and the recorded value was automatically converted from dB HL in dB SL, relative to the Masking Noise Threshold. The maskability was recorded as complete, partial or none.

For measuring of Residual inhibition (RI) the masking noise was applied at the MML (in dB HL) increased for 10 dB HL in duration of 60 seconds. RI was recorded as complete, partial or absent. It was also recorded for how long the tinnitus has changed (if at all).

3. Results

The total number of patients surveyed in our study was 212, 124 males (58.5%) and 88 females (41.5%). Unilateral tinnitus was present in 86 patients (40.6%) and bilateral tinnitus in 126 patients (59.4%). In cases with unilateral tinnitus, the localization of tinnitus was in the right ear in 33 patients (38.4%), and in the left ear in 53 patients (61.6%). In patients with bilateral tinnitus the right ear was tested in 45 patients (35.7%), and the left ear was tested in 81 patients (64.3%). So, the right ear was tested in a total of 78 patients (36.8%) and the left ear was tested in 134 patients (63.2%).

In terms of the tinnitus quality, a total of 163 patients had tonal tinnitus (76.9%). They described their tinnitus as whistling, hissing and cricket clicking. Majority of patients with tonal tinnitus (81%) had high-pitch whistling. A total of 49 patients had noise-like tinnitus (23.1%). They described their tinnitus as buzzing, humming, whooshing and roaring. There was no predominant tinnitus quality in this group.

We examined the relationship between psychoacoustic characteristics of tinnitus and several parameters of audiometry: the frequency of maximum hearing loss (the worst threshold), the frequency region of hearing loss, and the "edge frequency" of the audiogram. During pitch matching procedure a total of 25 patients (11.8%) experienced octave confusion.

In terms of the maximum hearing loss, tinnitus pitch corresponding to the frequency of the worst threshold was found in 79 patients (37.3%), and not corresponding in 133 patients (62.7%). We displayed the relationship between tinnitus pitch and the maximum hearing loss (Table 3). Tinnitus pitch of 4000 Hz was found corresponding to the worst threshold in more cases than other pitch-match frequencies.

Table 3. Relationship between tinnitus pitch and the maximum hearing loss.

Pitch-match frequency [Hz]	Corresponding		Not corresponding		Total	
	no.	[%]	no.	[%]	no.	[%]
125	1	0.5	12	5.7	13	6.1
250	–	0	13	6.1	13	6.1
500	–	0	10	4.7	10	4.7
750	–	0	1	0.5	1	0.5
1000	4	1.9	14	6.6	18	8.5
1500	–	0	2	0.9	2	0.9
2000	2	0.9	15	7.1	17	8
3000	5	2.4	17	8	22	10.4
4000	39	18.4	31	14.6	70	33
6000	5	2.4	9	4.2	14	6.6
8000	23	10.8	9	4.2	32	15.1
Total	79	37.3	133	62.7	212	100

Examination of the relationship between tinnitus pitch and the frequency range of hearing loss (or the frequency range of the worst hearing thresholds in cases with hearing loss at all frequencies) showed tinnitus pitch corresponding to the frequency range of hearing loss in 150 patients (70.8%), and not corresponding in 62 patients (29.2%). We found tinnitus pitch 125–500 Hz and 750–2000 Hz corresponding to the frequency range of hearing loss in 2.4% and 4.7%, respectively (Table 4). The majority of patients (63.7%) had tinnitus pitch from 3000 to 8000 Hz corresponding to the range of hearing loss. A statistical analysis shows that there is statistically significant difference between the number of patients with tinnitus pitch corresponding and not corresponding to the frequency range of hearing loss ($\chi^2 = 141.4$, $df = 2$, $p < 0.001$). The mean tinnitus pitch in all patients was 3545 Hz ± 2482.

Table 4. Relationship between tinnitus pitch and the frequency range of hearing loss.

Pitch-match frequency [Hz]	Corresponding		Not corresponding		Total	
	no.	[%]	no.	[%]	no.	[%]
125–500	5	2.4	31	14.6	36	17
750–2000	10	4.7	28	13.2	38	17.9
3000–8000	135	63.7	3	1.4	138	65.1
Total	150	70.8	62	29.2	212	100

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

The relationship between tinnitus pitch and the edge frequency of the audiogram, f_e, was also examined. We found tinnitus pitch corresponding to f_e in 35 patients (16.5%), and not corresponding in 177 patients (83.5%). Tinnitus pitch-match frequency of 2000 Hz was found corresponding to f_e in more cases than other pitch-match frequencies (Table 5).

Table 5. Relationship between tinnitus pitch and the edge frequency of the audiogram.

Pitch-match frequency [Hz]	Corresponding		Not corresponding		Total	
	no.	[%]	no.	[%]	no.	[%]
125	–	0	13	6.1	13	6.1
250	1	0.5	12	5.7	13	6.1
500	2	0.9	8	3.8	10	4.7
750	–	0	1	0.5	1	0.5
1000	5	2.4	13	6.1	18	8.5
1500	1	0.5	1	0.5	2	0.9
2000	13	6.1	4	1.9	17	8
3000	5	2.4	17	8	22	10.4
4000	6	2.8	64	30.2	70	33
6000	2	0.9	12	5.7	14	6.6
8000	–	0	32	15.1	32	15.1
Total	35	16.5	177	83.5	212	100

We displayed examples of audiograms of three patients with tinnitus pitch corresponding to the audiogram variables: maximum hearing loss (the worst threshold), the frequency range of hearing loss and the edge frequency of the audiogram (Fig. 1).

In Table 6 we summarized the results from relationship between tinnitus pitch and all audiometric variables tested in the study. In some cases tinnitus pitch corresponded to two audiometric variables.

Table 6. Tinnitus pitch corresponding to the audiometric variables.

Audiometric variables	125–500 Hz		750–2000 Hz		3000–8000 Hz		Total	
	no.	[%]	no.	[%]	no.	[%]	no.	[%]
Range of hearing loss	4	1.9	2	0.9	50	23.6	56	26.4
Maximum threshold/Range of hearing loss	1	0.5	6	2.8	72	34	79	37.3
Edge frequency	3	1.4	17	8	–	0	20	9.4
Edge frequency/Range of hearing loss	–	0	2	0.9	13	6.1	15	7.1
Neither variable	28	13.2	11	5.2	3	1.4	42	19.8
Total	36	17	38	17.9	138	65.1	212	100

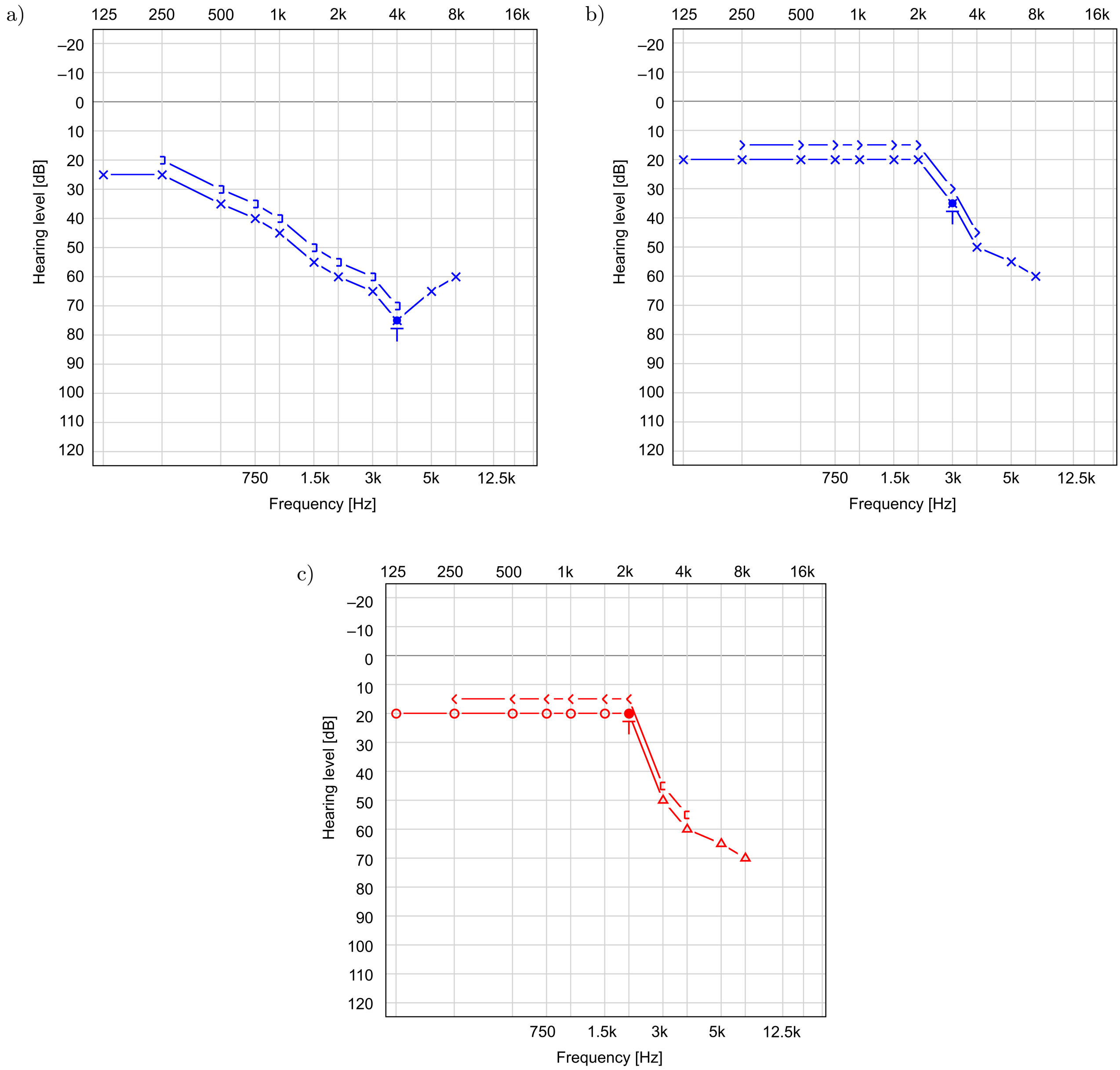

Fig. 1. Relationship between tinnitus pitch and audiogram variables: a) the worst threshold, b) the range of hearing loss, c) the edge frequency ("T" indicates tinnitus pitch-match frequency).

We also displayed the tinnitus pitch in relation to audiometric configuration (Table 7). Gradual slope audiometric configuration was more common than other types.

A total of 99 patients (46.7%) had gradual slope configuration. In terms of the pitch-match frequency, in cases of all tinnitus frequencies the gradual slope configuration was predominant except in tinnitus pitch 250 Hz, where flat and steep slope configuration were more frequent than gradual slope, in patients with tinnitus pitch 1000 Hz the flat configuration was predominant, and in cases of tinnitus pitch 3000 Hz, an equal number of patients had flat and gradual slope audiogram configuration.

Loudness matching was performed at tinnitus frequency in all patients. Sensation level was in the range from 1 to 12 dB SL. A total of 52 patients (24.5%) had sensation level from 1 to 3 dB SL, 140 patients (66%) had sensation level from 4 to 7 dB SL, and 20 patients (9.4%) had sensation level from 8 to 12 dB SL. The mean sensation level at tinnitus frequency was 4.9 dB SL ± 1.9.

Tinnitus loudness was also examined at 1000 Hz, the frequency outside the tinnitus region. The loudness matching was performed at the frequency of 1000 Hz in cases where that frequency was not the pitch-match frequency and the hearing threshold was ≤ 20 dB HL. From the total of 117 patients that met these criteria,

Table 7. Tinnitus pitch in different types of audiometric configuration.

Tinnitus pitch [Hz]	Flat		Gradual slope		Steep slope		Inverted “U” shape		Notch		Total	
	no.	[%]	no.	[%]	no.	[%]	no.	[%]	no.	[%]	no.	[%]
125	1	0.5	10	4.7	2	0.9	–	0	–	0	13	6.1
250	4	1.9	3	1.4	4	1.9	2	0.9	–	0	13	6.1
500	1	0.5	5	2.4	3	1.4	–	0	1	0.5	10	4.7
750	–	0	1	0.5	–	0	–	0	–	0	1	0.5
1000	7	3.3	5	2.4	4	1.9	1	0.5	1	0.5	18	8.5
1500	–	0	2	0.9	–	0	–	0	–	0	2	0.9
2000	4	1.9	6	2.8	4	1.9	–	0	3	1.4	17	8
3000	7	3.3	7	3.3	3	1.4	–	0	5	2.4	22	10.4
4000	10	4.7	34	16	7	3.3	–	0	19	9	70	33
6000	2	0.9	8	3.8	4	1.9	–	0	–	0	14	6.6
8000	8	3.8	18	8.5	–	0	–	0	6	2.8	32	15.1
Total	44	20.8	99	46.7	31	14.6	3	1.4	35	16.5	212	100

Table 8. Type of maskability and MML (dB SL).

Type of maskability	1–6		7–12		13–18		Total	
	no.	[%]	no.	[%]	no.	[%]	no.	[%]
Complete	114	59.1	67	34.7	5	2.6	186	96.4
Partial	2	1	3	1.6	2	1	7	3.6
Total	116	60.1	70	36.3	7	3.6	193	100

Fisher’s exact test ($p = 0.0097$).

Table 9. Type and duration of Residual inhibition (RI).

Type of RI	< 1 min		1–2 min		2–4 min		> 4		Total	
	no.	[%]	no.	[%]	no.	[%]	no.	[%]	no.	[%]
Complete	59	43.4	11	8.1	11	8.1	17	12.5	98	72.1
Partial	17	12.5	8	5.9	6	4.4	7	5.1	38	27.9
Total	76	55.9	19	14	17	12.5	24	17.6	136	100

Chi-square test ($p = 0.3156$).

data were available only for 78 patients. Mean sensation level at frequency of 1000 Hz was 13 dB SL ± 2.9. The level was in the range from 7 to 18 dB SL.

Psychoacoustic assessment of tinnitus also included determination of maskability. In total of 193 patients (91%) tinnitus was masked. The maskability was complete in 186 patients (96.4%) and partial in 7 patients (3.6%). In 19 patients (9%) the tinnitus was not masked. Minimum masking level (MML) was in the range from 1 to 18 dB SL. In total of 193 patients with maskable tinnitus, the mean MML was 6.3 dB SL ± 2.8. The results of MML are displayed in relation to the type of maskability (Table 8).

In patients with complete maskability, MML from 1 to 6 dB SL was predominant (59.1%). A statistical analysis shows that there is statistically significant difference between the type of maskability and MML ($p = 0.0097$). There was no case of exacerbation, an increase in the tinnitus sensation level in response to the masking noise presentation. Residual inhibition (RI) was tested in total of 193 patients with maskable tinnitus. We displayed type and duration of RI in all patients who experienced temporary suppression of tinnitus (Table 9).

RI was present in 136 patients (70.5%) and absent in 57 patients (29.5%). A statistical analysis shows that there is no statistically significant difference between the type and duration of RI ($\chi^2 = 3.5399$, $df = 3$, $p = 0.3156$).

4. Discussion

In our sample bilateral tinnitus was more common than unilateral tinnitus. Left ear was the test ear in most patients because left ear unilateral tinnitus was more common than right ear unilateral tinnitus, and in cases of bilateral tinnitus, tinnitus in the left ear was predominant. We can explain this by the fact that in our sample majority of patients with left ear unilateral tinnitus had acoustic trauma. During exposure to the gunfire noise, the left ear is more exposed to noise than the right ear, which is in the "acoustic shadow" of the head. Results from previous studies also showed more prevalent bilateral tinnitus than the unilateral one and more common left ear unilateral tinnitus (Ristovska *et al.*, 2015; Steinmetz *et al.*, 2009). In general, the percentage of left-sided tinnitus is greater than right-sided (Fabijańska *et al.*, 2012).

In terms of the tinnitus quality, most of the patients had tonal tinnitus. Norena *et al.* (2002) found most of the tinnitus spectra measured in their study exhibited at least one distinct peak. This suggests that in most cases, the tinnitus sensation had a distinct pitch. This is consistent with reports from tinnitus patients, who often describe their tinnitus as having a tonal component. When subjects are asked to adjust the frequency of an external pure tone to match the pitch of their tinnitus, they pick a frequency equal or close to that corresponding to the main peak of the tinnitus spectrum. Axelsson and Prasher (2000) also reported more common tonal tinnitus. According to Henry *et al.* (2004) tinnitus patients typically describe their tinnitus as "tonal", but the percept may in fact be more "spectral", i.e., containing a band, or bands of frequencies. In present study high-pitch whistling was predominant in patients with tonal tinnitus. It was also reported in a previous studies (Ristovska *et al.*, 2016; Crummer, Hassan, 2004; Martines *et al.*, 2010).

Pitch matching in present study included pure tones at frequencies from 125 to 8000 Hz. After completing the pitch matching to pure tones, the patient was asked if the tinnitus was more like tone or like noise (NBN). Pitch matching is an attempt to quantify tinnitus by its approximate frequency (Ibraheem, Hassaan, 2017). Even though the internal spectrum of tinnitus may be very broad, the use of pure tones as comparison stimuli appears as a reasonable methodological choice (Norena *et al.*, 2002). Despite criticism, pitch matching is widely used to estimate tinnitus frequency (McMillan *et al.*, 2014).

To determine the pitch of the tinnitus 2-AFC method was used. It is the most widely used method for tinnitus pitch matching due to its simplicity. Kostek and Poremski (2013) reported results from measuring the psychoacoustical properties of tinnitus by using the multimedia-based sound synthesizer. The experiments revealed capabilities of the new method.

For pitch matching we preferred presenting matching tones in the ipsilateral ear to avoid problems with binaural diplacusis (difference in pitch perception between ears). Results were confirmed with OCT. Small number of patients (11.8%) in our study experienced octave confusion. Kim *et al.* (2017) reported experienced octave confusion in 14.6% of the patients.

We examined the relationship between tinnitus pitch and several parameters of audiometry. In terms of the maximum hearing loss we found smaller number of tested ears with tinnitus pitch corresponding to the maximum hearing loss than those with tinnitus not corresponding. Only tinnitus pitch of 4000 and 8000 Hz was found corresponding in more cases than those not corresponding. In contrast to our results, Shecklmann *et al.* (2012) confirmed a relationship between tinnitus pitch and maximum hearing loss suggesting that tinnitus is rather a fill-in-phenomenon resulting from homeostatic mechanisms.

Examination of the relationship between tinnitus pitch and the frequency range of hearing loss or the frequency range of the worst hearing thresholds showed tinnitus pitch corresponding to the frequency region in more patients than not corresponding. In most patients tinnitus was matched to tones in the 3000–8000 Hz range. In most cases tinnitus pitch falls within the area of hearing loss. There is statistically significant difference between the number of patients with tinnitus pitch corresponding to some parameters of audiometry ($p < 0.001$). Norena *et al.* (2002) also reported that most of the components of the tinnitus spectrum fell in frequency ranges over which hearing thresholds were abnormally elevated in the subjects tested. There is a strong association between the pitch of tinnitus and the frequency range of abnormal hearing (Niewiarowicz, Kaczmarek, 2011). Tinnitus spectra covered the region of hearing loss with no preponderance of frequencies near the audiometric edge of normal hearing (Roberts *et al.*, 2006; 2008; Salvago *et al.*, 2012). In contrast to these results some authors did not find any relationship between the frequency of the tinnitus and frequency of hearing loss (Noroozian *et al.*, 2017).

The mean tinnitus pitch in our study was 3545 Hz ± 2482. Keppler *et al.* (2017) reported tinnitus pitch 4.10 kHz on average (SD = 2.59; range 0.125–8 kHz).

Our analysis of the relationship between tinnitus pitch and the edge frequency of the audiogram (f_e) showed tinnitus pitch corresponding to f_e only in 16.5% of the patients. In contrast to these results, Moore *et al.* (2010) found a clear relationship between the pitch of tonal tinnitus and f_e for subjects having mild-to-moderate sloping hearing loss with tonal tinnitus. In their study, generally, the mean matching frequency was close to f_e.

Tinnitus pitch was analyzed in relation to audiometric configuration. In majority of pitch-match frequencies gradual slope audiometric configuration was more common than other types. Kim *et al.* (2016) found that categorizing patients with tinnitus by audiometric shape may be important in analyzing the neurophysiologic characteristics of tinnitus. Most of the tinnitus patients in their study belonged to the Flat, High-frequency gently sloping and High-frequency steeply sloping groups.

We examined loudness matching at the tinnitus frequency versus at a normal-hearing frequency. Clinically, the most important attribute of tinnitus is its loudness. Reducing the loudness of tinnitus would provide therapeutic benefit. The two most common methods of assessing tinnitus loudness are loudness matching and loudness ratings (Henry, 2016). In our study loudness matching at tinnitus frequency showed mean sensation level of 4.9 dB SL (the range from 1 to 12 dB SL). Kim *et al.* (2017) reported similar findings. The mean matched tinnitus loudness in their study was 5.67 ±6.70 dB SL. Seimetz *et al.* (2016) reported that most of evaluated ears (80.1%) had tinnitus loudness between 0 dB SL and 19 dB SL. Although the patients often describe their tinnitus as very loud, in most of them, loudness of the tinnitus was only few dB above the hearing threshold. Moore (2014) concluded that tinnitus can be moderately loud even when the SL of the matching stimulus is low.

In our study loudness matching outside the tinnitus frequency showed higher sensation level than loudness matching at tinnitus frequency. Loudness estimates of tinnitus obtained by adjusting the intensity of a comparison tone are typically lower when the comparison frequencies are inside (2–3 dB) rather than outside (10–15 dB) the tinnitus region (Eggermont, Roberts, 2004). According to Henry (2016) tinnitus loudness is significantly underestimated when measured at the tinnitus frequency. Low-level tinnitus loudness matches might be explained by a phenomenon associated with sensorineural hearing loss – "loudness recruitment". Recruitment means a faster than normal growth of loudness between the elevated thresholds and high sound levels (Heinz *et al.*, 2005).

Testing that was done to determine how sound affects tinnitus included minimum masking levels and residual inhibition. Tinnitus was maskable in most patients in our study. That suggests that masking may be appropriate for some approaches to the tinnitus treatment. Results from pitch matching test may be applied for certain sound therapies in order to mask a specific region.

Maskability was complete in most patients. There is statistically significant difference between the type of maskability and MML ($p = 0.0097$). There was no case of exacerbation, an increase in the tinnitus sensation level in response to the masking noise presentation in our sample. Tinnitus maskability is an important prognostic factor of future tinnitus annoyance (Anderson *et al.*, 2001).

In our study, Residual inhibition was experienced in 70.5% of the patients. Vernon and Meikle (2003) reported that 88% of the patients display some form of RI. Complete RI was more common than partial RI and RI duration < 1 min was more common than RI > 1 min. There is no statistically significant difference between the type and duration of RI ($p = 0.3156$). The residual inhibition test is used for determining whether the tinnitus masking would be an applicable management course (Yang, Byun, 2016). The most helpful treatments based on this assumption include counseling and some form of sound therapy (Preece *et al.*, 2003). In audiology practice, masking noise generated by special masker devices is used to reduce tinnitus (Czyżewski, Skarżyński, 2007). In Tinnitus Retraining Therapy it is thought that sound generators provide a new type of stimulus which induces tonotopic reorganization of the auditory cortex (Poremski, Kostek, 2012).

5. Conclusion

Tinnitus pitch corresponded to the frequency range of hearing loss in the majority of patients. There was no relationship between tinnitus pitch and the edge frequency of the audiogram. Tinnitus pitch corresponding to the maximum hearing loss was in the range 3000–8000 Hz in most cases. Tinnitus sensation level was higher when the comparison frequency was outside than inside the tinnitus region. Tinnitus was maskable in the most of the patients and the majority of them experienced residual inhibition.

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