High frequency audiometry in tinnitus patients with normal hearing in conventional audiometry

Doaa M. Elmoazen, Hesham S. Kozou, Alaa A. Mohamed

Department of Otorhinolaryngology, Faculty of Medicine, Alexandria University, Alexandria, Egypt

Correspondence to Doaa M. Elmoazen, MD, 8 Kolyet Alteb Street, Raml Station, Alexandria, 21512, Egypt.
Tel: +20 3485 5414/+20 122 428 8678;
e-mail: doaa.elmoazen@alexmed.edu.eg

Received 3 June 2018
Accepted 7 August 2018

The Egyptian Journal of Otolaryngology
2018, 34:308–315

Context
Hearing loss is the most important risk factor of tinnitus, but this relation is not straightforward; some patients with severe tinnitus have normal hearing, whereas many patients with hearing loss do not have tinnitus.
Aims
The aim was to determine if high frequency audiometry (HFA) may reveal significant differences between normal hearing participants with and without tinnitus.
Settings and design
This is a case–control study.
Participants and methods
HFA was done on two groups of participants with normal hearing sensitivity. The first group was composed of 20 adults with tinnitus, whereas the control group was 15 age-matched and sex-matched participants, not suffering from tinnitus.
Statistical analysis
Data were analyzed using SPSS software package version 20.0. Significance of the results was judged at the 5% level. χ^2 with Fisher's exact as a correction, Kruskal–Wallis, Mann–Whitney, and Pearson's coefficient tests were used.
Results
HFA showed no significant difference between the two studied groups.
Conclusion
Tinnitus in normal hearing participants does not necessarily indicate corresponding damage in the cochlea

Keywords:
high frequency audiometry, normal hearing, tinnitus

Egypt J Otolaryngol 34:308–315

1012-5574

Introduction

Tinnitus is the detection of sound without an external source [1]. Most of tinnitus patients display impaired hearing threshold in the pure-tone audiometry (PTA), especially in the high frequency range [2–4]. Furthermore, the frequency spectrum of some individual's tinnitus matches the frequency range of the hearing impairment [5,6]. However, some tinnitus patients present with no detectable loss in the frequency range of the conventional PTA (125 Hz–8 KHz) [7].

The human ear has an auditory range that can reach up to 20 000 Hz. Frequencies between 9000 and 20 000 Hz are named extended high frequencies (EHFs) in the international literature [8]. The involvement of EHFs in auditory pathology is diverse. They affect detecting the location of the sound [9] and understanding language, especially in noisy surroundings [10]. They are also associated with age-related hearing loss, ototoxicity, and acoustic trauma.

It has been thought that a normal PTA does not exclude cochlear damage. Damage of hair cells that code for frequencies above 8 kHz cannot be detected by the conventional audiometry. Tinnitus patients whose audiograms are normal had more frequent cochlear dead regions [11], outer hair cell damage, and impaired hearing thresholds in the EHF region [12], when compared with control groups. In contrast, tinnitus may be induced purely in the central nervous system without damage to peripheral sensory organs [13,14].

In this study, we studied the role of high frequency audiometry (HFA) in the assessment of normal hearing tinnitus patients on conventional audiometry and whether it provides more relevant information about cochlear damage not proved by the conventional audiometry.

 DOI: 10.4103/ejo.ejo_44_18

Participants and methods

Participants

This study was carried on 20 adults with tinnitus aged up to 50 years old with no sex preference and with normal peripheral hearing sensitivity in frequencies 250–8000 Hz. Otologic or neurologic disease, middle ear problems, and patients with occupations with noise hazards were excluded. Fifteen age-matched and sex-matched participants with normal hearing and no tinnitus were involved as control group.

Methods

All participants were subjected to history taking, otoscopic examination, tympanometry to exclude middle ear problems, conventional audiometry (air, bone conduction thresholds, and mid octaves were done).

Pure-tone hearing thresholds at EHFs (9, 10, 11.2, 12.5, 14, and 16 kHz) were determined by the use of a MADSEN clinical audiometer (MADSEN Astera^2 from GN Otometrics, Taastrup, Denmark) with a Sennheiser HDA 200 closed circumaural earphone (Sennheiser Co., Wedemark, Germany). Thresholds for the conventional PTA (from 0.25 to 8 kHz) were obtained by the use of the same audiometer and a Telephonics TDH-39 supra-aural earphone (Telephonics Co., Farmingdale, New York, USA) [8].

Thresholds were assessed using the American National Standards Institute (ANSI) approach, which is an ascending technique beginning with an inaudible signal; the level was increased in 5 dB steps till a response occurred. After giving a response, the intensity was decreased by 10 dB, and another ascending series is started. The threshold was the lowest decibel hearing level at which responses occurred in at least 50% of ascending trials [15].

Normal hearing sensitivity was defined as a threshold of 20 dB HL at each frequency examined in the range from 0.25 to 8 kHz. To avoid inclusion of audiograms displaying minor dips, 3 and 6 kHz were also tested. Normal thresholds at EHFs were calculated by using mean +2 SD in the control group. Each age group was calculated separately. Participants were distributed into three age groups from 20 to 30 years, from 31 to 40 years, and from 41 to 50 years.

Pitch matching and loudness matching measurement

The first objective was to determine whether the tinnitus sounds more like pure tone or noise. Narrowband noise centered at pitch match frequency was presented with alternation with the pitch-matched tone and the patient was asked which sounds more like the tinnitus.

The pitch matching procedure is usually a two-alternative forced choice [16]. Two tones were presented to the patient and then asked to choose the one that most closely matched the tinnitus heard. This was continued until the match was made.

Tinnitus is mostly found to be a few decibels above a person's threshold for the frequency being tested [16,17]. For loudness matching, a frequency that was matched to the patient's tinnitus was presented at a level just below threshold and intensity was increased in a 1 dB step until the patient indicated a match [16].

Statistical analysis of the data

Data were analyzed using SPSS software package version 20.0 (SPSS Inc., Chicago, Illinois, USA). Significance of the obtained results was judged at the 5% level [18,19]. For demographic data, we used χ^2-test for categorical variables; Fisher's exact as a correction for χ^2 when more than 20% of the cells have expected count less than 5; and Student's *t*-test for normally distributed quantitative variables. For comparing HFA thresholds in different age groups Kruskal–Wallis test was used. For comparing HFA thresholds in control and cases Mann–Whitney test was used. To study the correlation between age and high frequency thresholds Pearson's coefficient was used in cases and control groups.

Results

In the current study, 20 tinnitus patients and 15 controls were enrolled. In the cases group, there were 4 males and 16 females, whereas in the control group 3 were males and 12 were females. Age was distributed into three age groups from 20 to 30 years, from 31 to 40 years, and from 41 to 50 years. In the controls 10 ears were tested in each age group. In the cases, 12 tested ears were in the first group, 14 tested ears in the second age group, and 14 tested ears were in the last age group.

Twelve patients were hearing tinnitus in the form of tones, whereas eight were hearing it as noise. All patients had bilateral tinnitus, six of them complained with right tinnitus more than left, nine patients complained with left more than right tinnitus, and in five patients tinnitus was equal on both ears.

Table 1 High frequency audiometry thresholds at different age groups in the controls

HF	Age (years)			*H*	*P*
	20–30	31–40	41–50		
9	*n*=10	*n*=10	*n*=10		
Minimum–maximum	10.0–35.0	5.0–30.0	5.0–40.0	0.539	0.764
Mean±SD	18.0±7.15	18.50±7.84	17.50±10.4		
Median	17.50	17.50	15.0		
10	*n*=10	*n*=10	*n*=10		
Minimum–maximum	5.0–40.0	5.0–35.0	5.0–50.0	1.553	0.460
Mean±SD	17.0±9.49	17.50±11.9	24.50±15.4		
Median	15.0	15.0	22.50		
11.2	*n*=10	*n*=10	*n*=10		
Minimum–maximum	10.0–45.0	5.0–40.0	5.0–55.0	1.205	0.547
Mean±SD	19.50±10.9	18.50±11.8	28.0±19.03		
Median	15.0	22.50	27.50		
12.5	*n*=10	*n*=10	*n*=10		
Minimum–maximum	10.0–40.0	5.0–55.0	10.0–65.0	4.196	0.123
Mean±SD	20.0±10.27	19.50±15.9	37.0±21.11		
Median	15.0	17.50	45.0		
14	*n*=10	*n*=10	*n*=8[a]		
Minimum–maximum	10.0–50.0	5.0–75.0	10.0–70.0	3.399	0.140
Mean±SD	22.0±11.8	29.50±21.0	41.25±22.6		
Median	17.50	25.0	42.50		
16	*n*=5	*n*=8[a]	*n*=6[a]		
Minimum–maximum	10.0–55.0	20.0–55.0	40.0–55.0	6.892*	0.032*
Mean±SD	26.0±16.50	35.63±16.8	49.17±7.36		
Median	22.50	35.0	52.50		
Significant between. groups	$P_{1=}$0.226, $P_{2=}$0.009*, $P_{3=}$0149				

H, *P*: *H* and *P* values for Kruskal–Wallis test, significance between groups was done using post-hoc test (Dunn's multiple comparisons test); HFA, high frequency audiometry; P_1, *P* value for comparison between 20–30 and 31–40 years; P_2, *P* value for comparison between 20–30 and 41–50 years; P_3: *P* value for comparison between 31–40 and 41–50 years. [a]Nonresponsing cases were excluded. *$P\leq0.05$, statistically significant at.

High frequency audiometry in the control group

Table 1 shows the relationship between age and HF thresholds in the control group showing mean±SD, median, minimum and maximum values.

Normal HFA thresholds were calculated by using mean +2 SD in the control group. Each age group was calculated separately. Normal hearing thresholds in HFA are shown in Table 2.

Table 2 Normal high frequency audiometry thresholds (Mean +2 SD) in control group for different age groups

Frequency (kHz)	Thresholds in age group 1 (20–30 years) (dB)	Thresholds in age group 2 (31–40 years) (dB)	Thresholds in age group 3 (41–50 years) (dB)
9	32.3	34.18	38.3
10	35.98	41.3	55.3
11.2	41.3	42.1	66.06
12.5	40.54	51.3	79.22
14	45.6	71.5	86.45
16	59	69.23	63.89

High frequency audiometry thresholds in cases

Table 3 shows comparison between the two studied groups according to high frequency thresholds. This comparison was detailed and classified according to different age groups in Tables 4–6. No significant difference was found between the two groups in terms of mean thresholds across the frequency range from 9 to 16 kHz .

Table 7 illustrates the number of nonresponding cases at frequency 14 kHz and 16 kHz reaching the maximum output of the audiometry. In control group, two participants showed no response at frequency of 14 KHz and six at 16 KHz. In cases group, four participants did not respond at 14 kHz and 16 at 16 kHz.

Of the 40 ears tested, only two ears showed high frequency hearing loss at 14 kHz and the remaining were normal in all other frequencies (putting in consideration that four ears out of 40 tested ears gave no response at 14 kHz, and 16 out of 40 tested ears did not give response at 16 kHz up to maximum sound level tested).

Table 3 High frequency audiometry thresholds in the two studied groups

	Control	Cases	*U*	*P*
9	*n*=30	*n*=40		
Minimum–maximum	5.0–40.0	5.0–40.0	594.50	0.947
Mean±SD	18.0±8.26	17.87±9.26		
Median	15.0	15.0		
10	*n*=30	*n*=40		
Minimum–maximum	5.0–50.0	5.0–45.0	510.00	0.282
Mean±SD	19.67±12.52	22.75±12.30		
Median	20.0	22.50		
11.2	*n*=30	*n*=40		
Minimum–maximum	5.0–55.0	5.0–65.0	485.00	0.169
Mean±SD	22.0±14.54	26.62±15.38		
Median	17.50	25.0		
12.5	*n*=30	*n*=40		
Minimum–maximum	5.0–65.0	5.0–70.0	466.50	0.111
Mean±SD	25.50±17.83	31.87±18.80		
Median	20.0	30.0		
14	*n*=28	*n*=36		
Minimum–maximum	5.0–75.0	5.0–75.0	371.50	0.072
Mean±SD	30.18±19.70	40.42±22.44		
Median	25.0	50.0		
16	*n*=24	*n*=24		
Minimum–maximum	10.0–55.0	5.0–55.0	266.50	0.654
Mean±SD	35.0±16.75	33.33±20.14		
Median	40.0	40.0		

U, *P*: *U* and P values for Mann–Whitney test for comparison between the two groups. Nonresponsing cases were excluded.

Table 4 High frequency audiometry thresholds in the two studied groups at age from 20 to 30 years

HF	Control (*n*=10)	Cases (*n*=12)	*U*	*P*
9				
Minimum–maximum	10.0–35.0	5.0–30.0	55.00	0.738
Mean±SD	18.0±7.15	17.08±9.40		
Median	17.50	15.0		
10				
Minimum–maximum	5.0–40.0	5.0–35.0	59.50	0.973
Mean±SD	17.0±9.49	18.75±12.45		
Median	15.0	15.0		
11.2				
Minimum–maximum	10.0–45.0	5.0–35.0	54.00	0.688
Mean±SD	19.50±10.92	17.50±10.77		
Median	15.0	17.50		
12.5				
Minimum–maximum	10.0–40.0	5.0–35.0	51.50	0.569
Mean±SD	20.0±10.27	16.67±10.30		
Median	15.0	17.50		
14				
Minimum–maximum	10.0–50.0	5.0–50.0	59.50	0.973
Mean±SD	22.0±11.83	24.17±17.69		
Median	17.50	27.50		
16				
Minimum–maximum	10.0–55.0	5.0–55.0	57.00	0.842
Mean±SD	26.0±15.60	27.08±19.71		
Median	22.50	32.50		

U, *P*: *U* and *P* values for Mann–Whitney test for comparing between the two groups.

Table 5 High frequency audiometry thresholds in the two studied groups at age from 31 to 40 years

HF	Control	Cases	*U*	*P*
9	*n*=10	*n*=14		
Minimum–maximum	5.0–30.0	5.0–25.0	57.00	0.435
Mean±SD	18.50±7.84	16.07±6.84		
Median	17.50	15.0		
10	*n*=10	*n*=14		
Minimum–maximum	5.0–35.0	5.0–40.0	56.00	0.405
Mean±SD	17.50±11.84	21.07±12.12		
Median	15.0	20.0		
11.2	*n*=10	*n*=14		
Minimum–maximum	5.0–40.0	5.0–40.0	53.00	0.313
Mean±SD	18.50±11.80	23.93±10.22		
Median	22.50	22.50		
12.5	*n*=10	*n*=14		
Minimum–maximum	5.0–55.0	10.0–45.0	38.50	0.063
Mean±SD	19.50±15.89	29.29±12.54		
Median	17.50	32.50		
14	*n*=10	*n*=14		
Minimum–maximum	5.0–75.0	5.0–55.0	43.00	0.108
Mean±SD	29.50±21.01	40.71±19.70		
Median	25.0	52.50		
16	*n*=8	*n*=10		
Minimum–maximum	20.0–55.0	10.0–55.0	37.00	0.783
Mean±SD	35.63±16.78	37.50±20.72		
Median	35.0	50.0		

U, *P*: U and *P* values for Mann–Whitney test for comparing between the two groups.

Table 6 High frequency audiometry thresholds in the two studied groups at age from 41 to 50 years

HF	Control	Cases	*U*	*P*
9	*n*=10	*n*=14		
Minimum–maximum	5.0–40.0	5.0–40.0	58.50	0.495
Mean±SD	17.50±10.34	20.36±11.17		
Median	15.0	20.0		
10	*n*=10	*n*=14		
Minimum–maximum	5.0–50.0	10.0–45.0	59.50	0.536
Mean±SD	24.50±15.36	27.86±11.39		
Median	22.50	27.50		
11.2	*n*=10	*n*=14		
Minimum–maximum	5.0–55.0	15.0–65.0	47.50	0.185
Mean±SD	28.0±19.03	37.14±17.40		
Median	27.50	30.0		
12.5	*n*=10	*n*=14		
Minimum–maximum	10.0–65.0	20.0–70.0	45.00	0.141
Mean±SD	37.0±21.11	47.50±18.16		
Median	45.0	55.0		
14	*n*=8	*n*=10		
Minimum–maximum	10.0–70.0	25.0–75.0	19.00	0.054
Mean±SD	41.25±22.64	59.50±16.06		
Median	42.50	65.0		
16	*n*=6	*n*=2		
Minimum–maximum	40.0–55.0	50.0–50.0	5.00	0.724
Mean±SD	49.17±7.36	50.0±0.0		
Median	52.50	50.0		

U, *P*: *U* and *P* values for Mann–Whitney test for comparing between the two groups.

Table 7 Comparison between the two studied groups according to nonresponding cases

Nonresponding cases	Control (n=30) [n (%)]	Cases (n=40) [n (%)]	χ^2	P
HF 14	2 (6.7)	4 (10.0)	0.243	0.694
HF 16	6 (20.0)	16 (40.0)	3.182	0.074

Table 9 Correlation between age and high frequency thresholds in control group

	N	Age (years)	
		r	P
HF 9	30	0.044	0.816
HF 10	30	0.383*	0.036*
HF 11.2	30	0.394*	0.031*
HF 12.5	30	0.561*	0.001*
HF 14	28	0.522*	0.004*
HF 16	24	0.546*	0.006*

r, Pearson's coefficient. *P≤0.05, statistically significant.

Correlation between high frequency audiometry thresholds and age in control and cases

Tables 8 and 9 demonstrate the correlation between age and high frequency thresholds in cases and controls respectively, showing statistically significant positive correlation between age and HFA thresholds in cases starting from frequency 11.2 kHz and in control group starting from frequency 10 kHz.

Pitch matching and loudness matching

Table 10 shows the distribution of the studied cases according to pitch matching and loudness matching.

Tinnitus pitch ranged from 1 to 9 kHz with a mean of 3.24 kHz. Loudness matching ranged from 14 dBHL up to 60 dBHL with mean of 31.42 dBHL.

Discussion

The main risk factor of tinnitus is HL [20]. However, this association is not simple or straightforward [21]. Some participants with troublesome tinnitus have audiometrically normal hearing and, conversely, many participants with hearing loss do not report tinnitus [20].

It has been argued that a normal PTA does not necessarily exclude cochlear damage [11]. Thus, the aim of this study was to explore the results of the HFA and see whether it provides additional information in tinnitus patients with normal hearing on conventional audiometry.

High frequency audiometry thresholds in normal participants

Normal HFA thresholds were calculated by using mean +2 SD in the control group. Each age group was calculated separately (from 20 to 30 years, from 31 to 40 years, and from 41 to 50 years).

Table 8 Correlation between age and high frequency thresholds in cases group

	N	Age (years)	
		r	P
HF 9	40	0.174	0.284
HF 10	40	0.282	0.078
HF 11.2	40	0.509*	0.001*
HF 12.5	40	0.657*	<0.001*
HF 14	36	0.672*	<0.001*
HF 16	24	0.405*	0.050*

Table 10 Distribution of the studied cases according to pitch matching and loudness matching (n=20)

	n (%)
Pitch matching (KHz)	
1	2 (10.0)
1.5	5 (25.0)
2	2 (10.0)
3	4 (20.0)
4	4 (20.0)
6	2 (10.0)
9	1 (5.0)
Minimum–maximum	1.0–9.0
Mean±SD	3.13±2.04
Median	3.0
Loudness matching	
Minimum–maximum	14.0–60.0
Mean±SD	31.42±12.87
Median	29.0

All participants were able to respond to the maximum sound levels tested up to 12.5 kHz in the EHF range. The number of participants not responding to the maximum sound levels presented above 12.5 kHz increased as the frequency increased, especially in older age groups.

The absence of response to EHF tested in the older age groups is in accordance with other authors' reports with respect to the general tendency of a gradual decrease of hearing sensitivity at higher frequencies and with increasing age [22,23]. The shift occurs first at the highest frequencies and then progresses to lower frequencies as the participants increase in age [8].

The dispersal of the data with increasing frequency demonstrates the great variability of values present in the general population. This could be explained by individual differences in the aging process, dietary quality, and individual nutrient intake. Also environmental factors influence hearing outcomes like noise exposure, accumulation of ototoxic materials, and the aging process itself [8].

These results were supported by another study that enrolled 645 participants from healthy volunteers. They were divided into seven age groups at 10-year intervals [8]. They showed increase in the hearing threshold as frequencies increased over the conventional and EHF range and some participants started giving no response starting from 11.2 kHz [8].

High frequency audiometry thresholds in tinnitus patients

HFA didn't reveal any significant difference in mean thresholds between our group of normal hearing tinnitus patients, compared with a matched group of tinnitus-free controls suggesting that tinnitus with a normal conventional audiogram does not reflect detectable cochlear damage in the EHF range.

Supporting our results, a study done by Barnea included 17 tinnitus patients aged 21–45 years (mean=35 years) with normal hearing and 17 participants as control group based on the mean thresholds across the range from 2 to 8 kHz in each ear. Their results also showed that no significant differences were found between the two groups, in terms of mean thresholds across the frequency range from 9 to 20 kHz [24].

A study by Shim *et al.* [25] enrolled 18 tinnitus patients, who had a hearing levels less than 25 dB at frequencies of 250–8000 Hz. The HFA was performed, and the mean hearing thresholds at 10, 12, 14, and 16 kHz of each tinnitus ear were compared with those of the 10 age-matched and sex-matched normal ears. In this study,12 had significantly increased hearing thresholds at more than one of the four high frequencies compared with the normal group. When they assessed results according to the frequency, they found that eight patients had decreased hearing ability at 10 kHz, 10 at 12 kHz, eight at 14 kHz, and four at 16 kHz. The high number of abnormal cases compared with our study may be due to their use of the mean as normative value, whereas in the current study we used 2 SD from the mean.

A possible explanation of tinnitus with no hearing loss may be the affection of the central nervous system with no damage to the peripheral sensory organs. In most tinnitus patients, the afferent signals are affected by damage to peripheral sensory organs, and plastic changes might follow in the central auditory pathway, which may induce spontaneous activity. However, a decrease in afferent acoustic signals is not essential [13,14]. For example, in individuals with somatic tinnitus syndrome, somatic stimuli may stimulate a specific area of the acoustic center. This may cause tinnitus, which occurs regardless of hearing ability [25].

Furthermore, in patients without a decrease in hearing ability, damage to the hair cells in peripheral sensory organs may be mild and biochemical changes preceding structural damage in the hair cells may induce tinnitus [26].Additionally, HFA had employed an evoking stimulus, and tinnitus is argued to be caused by abnormal spontaneous hyperactivity in the auditory pathways. Demonstrable differences between normal listeners with and without tinnitus might be reflected in the spontaneous activity of the auditory pathways [24].

Pitch matching and loudness matching

There was wide range of intersubject variability in tinnitus pitch (1–9 kHz). Tinnitus loudness at the tinnitus pitch frequency was found to have a mean of 31.42 dBSL (ranging from 14 dB up to 60 dBSL). A study done by Barnea [24], found pitch matching in the range from 0.25 to 16 kHz with a mean of 6.8 kHz and loudness matching mean of 15.3 dB SL with a range of 0–45 dB SL. This variability in the tinnitus pitch of the participants with normal hearing sensitivity might partially be caused by the fact that these participants struggle in establishing their tinnitus pitch [24].

Conclusion

The results of this study suggest that tinnitus with a normal conventional audiogram does not necessarily reflect appreciable cochlear damage in the EHFs, which might suggest a further central cause for tinnitus.

Recommendations

Future studies on participants with normal hearing sensitivity, particularly on the spontaneous activity of the auditory pathways, are needed to provide further information about tinnitus in normal listeners.

Financial support and sponsorship

Nil.

Conflicting of interest

There are no conflicts of interest.

References

1 Ahlf S, Tziridis K, Korn S, Strohmeyer I, Schulze H. Predisposition for and prevention of subjective tinnitus development. PLoS One 2012; 7:e44519.

2 Kim DK, Park SN, Kim HM, Son HR, Kim NG, Park KH, *et al.* Prevalence and significance of high-frequency hearing loss in subjectively normal-hearing patients with tinnitus. Ann Otol Rhinol Laryngol 2011; 120:523–528.

3 Konig O, Schaette R, Kempter R, Gross M. Course of hearing loss and occurrence of tinnitus. Hear Res 2006; 221:59–64.

4 Martines F, Bentivegna D, Martines E, Sciacca V, Martinciglio G. Assessing audiological, pathophysiological and psychological variables in tinnitus patients with or without hearing loss. Eur Arch Otorhinolaryngol 2010; 267:1685–1693.

5 Norena A, Micheyl C, Chery-Croze S, Collet L. Psychoacoustic characterization of the tinnitus spectrum: implications for the underlying mechanisms of tinnitus. Audiol Neurootol 2002; 7:358–369.

6 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:e34878.

7 Schaette R, McAlpine D. Tinnitus with a normal audiogram: physiological evidence for hidden hearing loss and computational model. J Neurosci 2011; 31:13452–13457.

8 Rodriguez Valiente A, Trinidad A, Garcia Berrocal JR, Gorriz C, Ramirez Camacho R. Extended high-frequency (9–20 kHz) audiometry reference thresholds in 645 healthy subjects. Int J Audiol 2014; 53:531–545.

9 Best V, Carlile S, Jin C, van Schaik A. The role of high frequencies in speech localization. J Acoust Soc Am 2005; 118:353–363.

10 Rodriguez Valiente A, Perez Sanz C, Gorriz C, Juarez A, Monfort M, Garcia Berrocal JR, *et al.* Designing a new tool for hearing exploration. Acta Otorrinolaringol Esp 2009; 60:43–48.

11 Weisz N, Muller S, Schlee W, Dohrmann K, Hartmann T, Elbert T. The neural code of auditory phantom perception. J Neurosci 2007; 27:1479–1484.

12 Fabijanska A, Smurzynski J, Hatzopoulos S, Kochanek K, Bartnik G, Raj-Koziak D, *et al.* The relationship between distortion product otoacoustic emissions and extended high-frequency audiometry in tinnitus patients. Part 1: normally hearing patients with unilateral tinnitus. Med Sci Monit 2012; 18:765–770.

13 Kaltenbach JA, Zhang J, Finlayson P. Tinnitus as a plastic phenomenon and its possible neural underpinnings in the dorsal cochlear nucleus. Hear Res 2005; 206:200–226.

14 Saunders JC. The role of central nervous system plasticity in tinnitus. J Commun Disord 2007; 40:313–334.

15 American National Standards Institute (ANSI). Methods for manual puretone thresholds audiometry. New York: ANSI; 2004.

16 Goldstein B, Shulman A. Tinnitus evaluation. In Shulman A, Aran J, Tonndorf J, Feldman H, Vernon JA, editors. Tinnitus: diagnosis/treatment. San Diego: Singular Publishing Group, Inc 1997. 293–318

17 Henry JA, Meikle MB. Psychoacoustic measures of tinnitus. J Am Acad Audiol 2000; 11:138–155.

18 Kirkpatrick LA, Feeney BC. A simple guide to IBM SPSS statistics for version 20.0. Student ed. Belmont: Wadsworth, Cengage Learning 2013.

19 Kotz S, Balakrishnan N, Read CB, Vidakovic B. Encyclopedia of statistical sciences. 2nd ed. Hoboken: Wiley-Interscience 2006.

20 Nondahl DM, Cruickshanks KJ, Huang GH, Klein BE, Klein R, Nieto FJ, *et al.* Tinnitus and its risk factors in the Beaver Dam offspring study. Int J Audiol 2011; 50:313–320.

21 Davis A, El Rafaie A. Epidemiology of tinnitus. In: Tyler RS, editor. Tinnitus handbook. San Diego: Singular, Thomson Learning; 2000. 1–23

22 Frank T. High-frequency hearing thresholds in young adults using a commercially available audiometer. Ear Hear 1990; 11:450–454.

23 Wiley TL, Cruickshanks KJ, Nondahl DM, Tweed TS, Klein R, Klein R, *et al.* Aging and high-frequency hearing sensitivity. J Speech Lang Hear Res 1998; 41:1061–1072.

24 Barnea G, Attias J, Gold S, Shahar A. Tinnitus with normal hearing sensitivity: extended high-frequency audiometry and auditory-nerve brain-stem-evoked responses. Audiology 1990; 29:36–45.

25 Shim HJ, Kim SK, Park CH, Lee SH, Yoon SW, Ki AR, *et al.* Hearing abilities at ultra-high frequency in patients with tinnitus. Clin Exp Otorhinolaryngol 2009; 2:169–174.

26 Henry JA, Dennis KC, Schechter MA. General review of tinnitus: prevalence, mechanisms, effects, and management. J Speech Lang Hear Res 2005; 48:1204–1235.