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Investigation of extended high-frequency hearing in adults: a cross-sectional study

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Abstract

Background This study aimed to present normative data on extended high-frequency (EHF) thresholds in healthy adults.

Methods This observational study included 200 individuals (400 ears) with normal hearing based on the four frequency pure-tone average. Participants ranged in age from 18 to 70 years and were divided into five age groups. Each group consisted of 40 participants (80 ears), with an equal number of males and females. The preliminary assessments involved acoustic immittance tests, otoacoustic emission evaluation, pure-tone audiometry, and speech audiometry. Subsequently, EHF audiometry was performed to assess EHF thresholds within and between groups based on ear side (right vs. left), gender, and age.

Results The study found no statistically significant difference in EHF thresholds between the right and left ears across all groups ($p > 0.05$). However, when the effect of gender was analyzed, a statistically significant difference in EHF thresholds was observed in the 30–39, 40–49, and 60–70 age groups ($p < 0.05$). A statistically significant difference was also found between the groups for each EHF ($p < 0.05$). EHF thresholds were observed to increase with age. The frequency most strongly correlated with age was 12.5 kHz ($r = 0.828$, $p < 0.001$).

Conclusions This study has demonstrated the effects of gender and age on EHF thresholds. The normative data presented in this study may contribute to the early detection, prevention and treatment of pathologies affecting the EHF thresholds.

Keywords Hearing tests, Auditory threshold, Audiometry, High-frequency hearing loss, Aging, Adult

Introduction

Early diagnosis, treatment and prevention of hearing loss are important. Conventional pure-tone audiometry measures hearing within the 125 Hz-8 kHz range. However, human hearing extends up to 20 kHz [1]. Frequencies above 8 kHz (9–20 kHz) are known as extended high-frequencies (EHF). The measurement of EHF thresholds has become possible with the advancement of clinical audiometers and headphones capable of delivering sound at adequate sound pressure levels (SPL). EHF audiometry has software and calibration to assess the EHF range. In addition to pure-tone stimuli, narrowband noise or warble stimuli can also be used as stimulus [1, 2].

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EHF audiometry has been used less than conventional pure-tone audiometry over the years. One reason for this is that the frequency range measured by conventional pure-tone audiometry covers most of the speech frequencies, which are the fundamental octaves. However, considering that EHF plays an important role in providing cues such as speech understanding and sound localization in noise, EHF audiometry has an important role in clinical practice [1, 3, 4].

The assessment of EHF thresholds is highly valuable for the early diagnosis of hearing loss in various pathologies. EHF audiometry plays a crucial role in detecting, assessing, and monitoring early ototoxic damage [5, 6]. Ototoxic agents, such as cisplatin, have a primary effect on the hair cells in the basal region of the cochlea, with changes in hearing first appearing in the EHF range [7, 8]. Additionally, EHF assessment is useful in detecting noise-induced hearing loss. Since the basal region of the cochlea is particularly vulnerable to acoustic trauma, hearing loss is expected in the EHF range in addition to 4–6 kHz [9, 10].

Asymmetry between the ears is not expected in a healthy hearing system. Studies have generally reported no significant difference in EHF thresholds between the right and left ears [11, 12]. However, the effect of gender on EHF thresholds varies between studies [1, 13, 14]. When considering the effect of age, a significant increase in EHF thresholds with aging has been reported in many studies [1, 12].

Conventional pure-tone audiometry thresholds for individuals with normal hearing are published in International Organization for Standardization (ISO) 7029 [11, 15]. Further references in the 8–16 kHz range can be found in ISO 389-5 [16]. However, these standards are limited by relatively small sample sizes, lack of age- and gender-specific data, and restricted age ranges. Although subsequent revisions expanded the age range up to 80 years for 9–12.5 kHz range [11], comprehensive normative data extending to 20 kHz, particularly for adults aged > 40 years remain scarce.

Therefore, this study aimed to present normative data on EHF thresholds extending up to 20 kHz in healthy adults, with a specific focus on examining the effects of gender, and age—particularly addressing the data scarcity in adults aged > 40 years —on these thresholds, while also verifying interaural symmetry.

Materials and methods

Study design and participants

This cross-sectional and observational study was held at Marmara University Faculty of Medicine, Department of Audiology. Ethical approval was obtained from the Ethics Committee of Marmara University Faculty of Medicine (date: 08/01/2021 - protocol no: 09.2021.76). This study was conducted in accordance with the Declaration of Helsinki and a signed informed consent form was obtained from all participants.

The study included 200 subjects (400 ears) with normal hearing (≤ 25 dB HL) as measured by four-frequency pure-tone average (PTA-0.5, 1, 2, 4 kHz), aged from 18 to 70 years. Participants were divided into five age groups: 18–29, 30–39, 40–49, 50–59, and 60–70 years. Each group consisted of 40 participants (80 ears), with an equal number of males and females. The data obtained from the participants were statistically analyzed within and between the groups.

Inclusion criteria were having bilateral ipsilateral and contralateral acoustic reflexes (at 0.5, 1, 2 kHz) in addition to the type A tympanogram, aged between 18 and 70 years, having PTA ≤ 25 dB HL, having distortion product otoacoustic emissions (DPOAE) in at least three frequency bands. Exclusion criteria included not meeting any inclusion criteria, a history of ototoxic drug use or noise exposure, prior ear surgery, having a mental, physical, or neurological condition that prevented the testing.

Data collection

After the detailed anamnesis, participants underwent acoustic immittancemetry tests (tympanometry and acoustic reflex measurement) using the AT235 immittance meter (Interacoustics, Middelfart, Denmark). A 226 Hz probe tone was used. Tympanogram results were analyzed according to Jerger classification [17]. EZ-Screen 2 software paired with an Echoport ILO292 USB-I system (Otodynamics, United Kingdom) was used to record DPOAEs at six frequencies (1, 1.5, 2, 3, 4, and 6 kHz). DPOAE was considered present if a response was obtained in at least three frequencies at a signal-to-noise ratio of 6 dB.

Pure-tone and EHF audiometry were conducted in a double-walled sound-attenuated test chamber compliant with Industrial Acoustic Company standards, using an AC-440 clinical audiometer (Interacoustics, Middelfart, Denmark). Conventional pure-tone audiometry included air conduction thresholds between 0.125 and 8 kHz using TDH-39 supraaural headphones, bone conduction thresholds between 0.5 and 4 kHz using B-71 bone vibrator, and EHF thresholds between 9 and 20 kHz using KOSS R/80 circumaural headphones. The maximum output level (MOL) of EHF on the clinical audiometer is 90, 95, 95, 80, 75, 60, 40, and 15 dB HL, respectively. If response rate was 100% at the evaluated frequencies, the term “full response” was used. Most studies report data in dB SPL due to the lower MOL of EHF audiometry compared to conventional pure-tone audiometry [1, 13, 14, 18–26]. However, the thresholds obtained in this study were recorded in dB HL.

The pure-tone stimulus was used in the evaluations. Hearing thresholds were determined by the modified Hughson-Westlake method. Goodman's scale was preferred to classify hearing as normal based on PTA [27]. Speech audiometry included measurement of the speech recognition threshold (SRT) and the speech discrimination score (SDS). All evaluations took approximately 40 min.

Statistical analysis

Data were analyzed using IBM SPSS Statistics for Windows, Version 23.0 (IBM Corp., Armonk, NY, USA). A p value < 0.05 was considered statistically significant. Categorical variables are presented as counts and percentages ("n" and "%"). The skewness and kurtosis values of continuous variables ranged from − 1.5 to + 1.5, indicating that the data met the assumption of normality [28].

Due to the normal distribution of the groups, the two-tailed independent samples t-test was used for within-group comparisons based on ear side and gender. Comparisons of EHF thresholds between groups were conducted using one-way analysis of variance (ANOVA). The Games-Howell or Tukey post-hoc tests were applied according to the Levene test results to determine specific group differences. Additionally, Pearson's correlation test was performed to assess the relationship between EHF thresholds and age. Statistical comparisons between groups were not conducted for frequencies where the response rate at MOL was below 20% [12].

Results

Study population

The mean age of the 18–29 age group was 25.18 (SD = 2.78), the mean age of the 30–39 age group was 33.77 (SD = 2.77), the mean age of the 40–49 age group was 43.6 (SD = 2.91), the mean age of the 50–59 age group was 52.45 (SD = 2.27), the mean age of the 60–70 age group was 64.05 (SD = 3.73), and the mean age of all participants was 43.81 (SD = 13.99). The total number of male and female participants, as well as the number of right/left ears in each group, was equal. The acoustic immittance evaluation revealed type A tympanograms and present ipsilateral/contralateral acoustic reflexes for all patients. DPOAEs were also present in all patients.

Conventional pure-tone audiometry assessment

The descriptive statistics of air conduction hearing thresholds ranging from 125 Hz to 8 kHz, bone conduction hearing thresholds ranging from 500 Hz to 4 kHz, and speech audiometry findings are presented in Table 1. The mean threshold curves within the 125 Hz-8 kHz range for the age groups are illustrated in Fig. 1.

Extended high-frequency audiometry assessment

In the threshold assessment with EHF audiometry, a full response was obtained from the 18–29 and 30–39 age groups up to 18 kHz; at 20 kHz, response rates were 47.5% and 46.25%, respectively. The 40–49 age group showed full response up to 16 kHz; at 18 and 20 kHz, response rates were 96.25% and 38.75%, respectively. In the 50–59 age group, full response was obtained up to 14 kHz; at 16, 18 and 20 kHz, response rates were 73.75%, 61.25%, and 32.5%, respectively. In the 60–70 age group,

Table 1 Descriptive statistics of pure-tone audiometry and speech audiometry results for all age groups

Variables	Hearing thresholds (dB HL) for all age groups M (SD)				
	18–29 years	30–39 years	40–49 years	50–59 years	60–70 years
PTA	4.58 (3.27)	5.05 (4.62)	8.59 (4.62)	13.52 (5.63)	15.79 (5.68)
SRT	4.06 (2.99)	4.00 (3.85)	7.06 (4.69)	10.63 (5.53)	12.13 (5.56)
SDS	97.85 (3.11)	97.45 (3.56)	96.40 (4.30)	94.55 (4.42)	94.00 (4.89)
BC 500 Hz	0.25 (4.56)	1.31 (4.69)	4.31 (6.15)	8.44 (6.24)	10.50 (6.24)
BC 1 kHz	-3.31 (3.08)	-0.88 (3.63)	2.13 (7.15)	5.56 (6.94)	9.25 (7.38)
BC 2 kHz	-0.25 (5.95)	1.81 (6.62)	2.63 (5.57)	8.63 (6.61)	11.63 (7.28)
BC 4 kHz	0.31 (5.12)	1.63 (7.11)	6.25 (7.44)	13.94 (8.59)	19.13 (9.67)
AC 125 Hz	8.75 (5.19)	7.56 (6.01)	10.38 (5.61)	15.69 (8.18)	15.81 (7.48)
AC 250 Hz	8.75 (5.48)	6.44 (6.17)	9.25 (5.40)	14.81 (8.36)	15.19 (6.72)
AC 500 Hz	5.25 (4.70)	4.63 (4.95)	7.69 (6.06)	12.00 (7.78)	12.44 (6.41)
AC 1 kHz	2.94 (4.11)	3.75 (4.10)	8.25 (6.66)	10.00 (6.36)	12.44 (6.66)
AC 2 kHz	5.06 (5.25)	5.81 (7.00)	8.13 (5.87)	13.50 (6.86)	14.75 (7.79)
AC 4 kHz	5.06 (5.37)	6.00 (8.55)	10.25 (8.15)	18.69 (9.99)	23.56 (10.10)
AC 6 kHz	6.00 (8.98)	11.13 (8.60)	12.25 (7.95)	23.88 (7.83)	31.31 (10.46)
AC 8 kHz	10.00 (7.38)	10.19 (9.39)	10.69 (7.82)	23.50 (10.48)	33.88 (12.58)

M: Mean, SD: Standard deviation, Hz: Hertz, kHz: Kilohertz, dB HL: Decibels hearing level, PTA: Pure-tone average of four frequency air conduction thresholds (500 Hz, 1 kHz, 2 kHz, 4 kHz), AC: Air conduction, BC: Bone conduction, SRT: Speech recognition threshold, SDS: Speech discrimination score

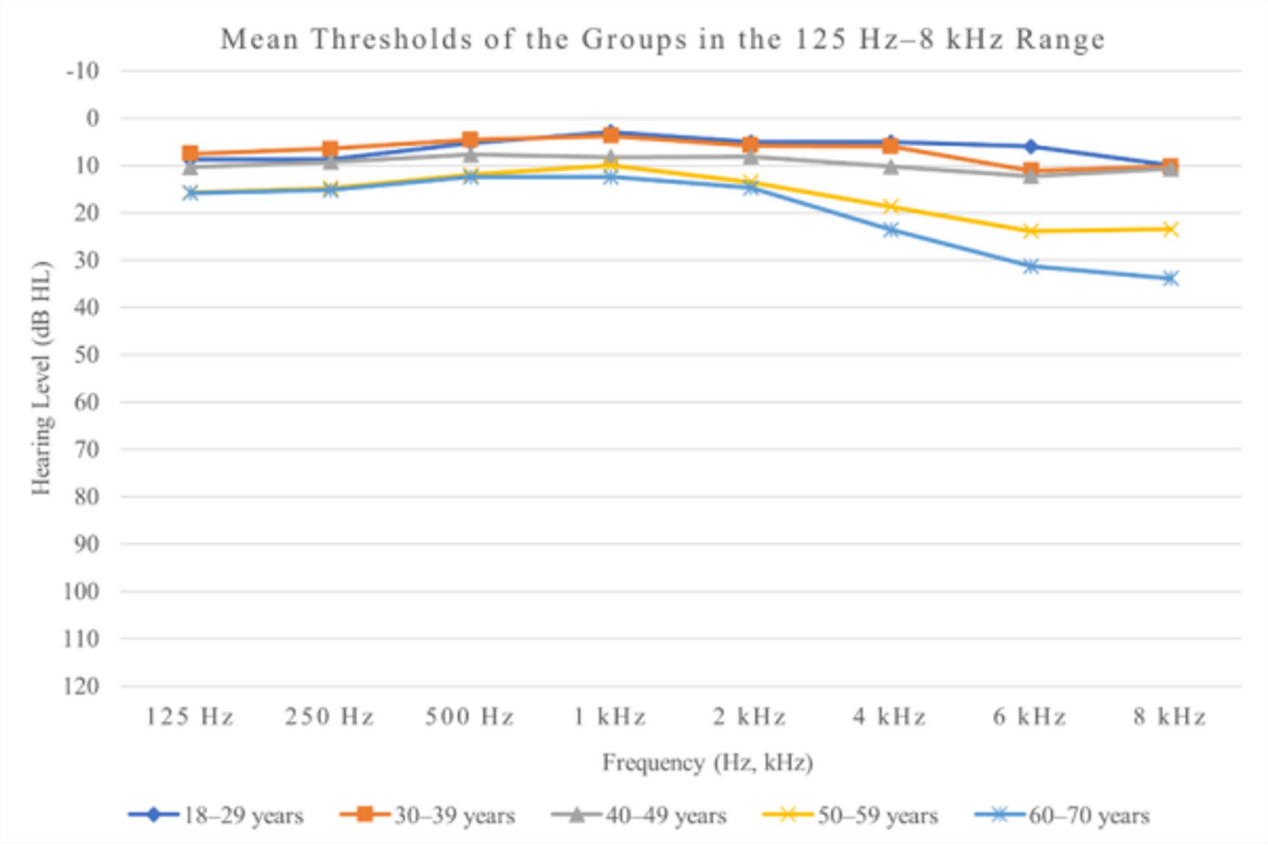

Fig. 1 The mean threshold curves within the 125 Hz–8 kHz range for the age groups

full response was obtained up to 11.25 kHz; response rates were 92.5% at 12.5 kHz, 76.25% at 14 kHz, 43.75% at 16 kHz, 38.75% at 18 kHz, and 12.5% at 20 kHz. The EHF response percentages are shown in the Fig. 2. There were no statistically significant differences in terms of ear side in any of the groups ($p > 0.05$). Comparison of EHF thresholds between the left and right ears across all age groups are presented in Table 2.

Gender distribution did not differ significantly in the 18–29 age group ($p > 0.05$). In the 30–39 age group, females had significantly higher thresholds than males at 16 kHz ($p = 0.005$, Cohen's d = 0.65), 18 kHz ($p < 0.001$, Cohen's d = 0.82), and 20 kHz ($p = 0.004$, Cohen's d = 1.03). In the 40–49 age group, males had significantly higher thresholds than females at 9 kHz ($p < 0.001$, Cohen's d = 0.84) and 10 kHz ($p = 0.004$, Cohen's d = 0.66). In the 50–59 age group, however, there was no statistically significant difference between genders ($p > 0.05$). In the 60–70 age group, males had significantly higher thresholds at 14 kHz than females ($p = 0.013$, Cohen's d = 0.7). Comparison of EHF thresholds between males and females across all age groups are presented in Table 3.

A comparison of the EHF thresholds among the age groups revealed statistically significant differences at 9–18 kHz (all $p < 0.001$) and at 20 kHz ($p = 0.015$). To identify which age groups exhibited these differences, Games-Howell and Tukey HSD post hoc analyses were applied according to the Levene test. The results indicated that the 9 kHz thresholds of the 18–29 and 30–39 age groups were statistically lower than those of the 40–49 age group ($p = 0.003$ and $p = 0.029$, respectively). Similarly, the 10 kHz thresholds of the 18–29 and 30–39 age groups were statistically lower than those of the 40–49 group ($p < 0.001$, $p = 0.011$, respectively). Furthermore, the 9 and 10 kHz thresholds of the 18–29, 30–39, and 40–49 age groups were statistically lower than those of the 50–59 and 60–70 groups (all $p < 0.001$). The 50–59 age group also had significantly lower thresholds at 9 and 10 kHz compared to the 60–70 group (both $p < 0.001$).

The 11.25 and 12.5 kHz thresholds of the 18–29 age group were statistically lower than those of the 30–39 age group ($p < 0.018$, $p < 0.001$, respectively). Additionally, the 11.25 kHz thresholds of the 18–29 and 30–39 age groups were found to be statistically lower than those of the 40–49 age group ($p < 0.001$, $p = 0.009$, respectively). Similarly, the 12.5 kHz thresholds of the 18–29 and 30–39 age groups were found to be statistically lower than those of the 40–49 age group (both $p < 0.001$). Furthermore, the 11.25 and 12.5 kHz thresholds of the 18–29, 30–39, and 40–49 age groups were found to be statistically

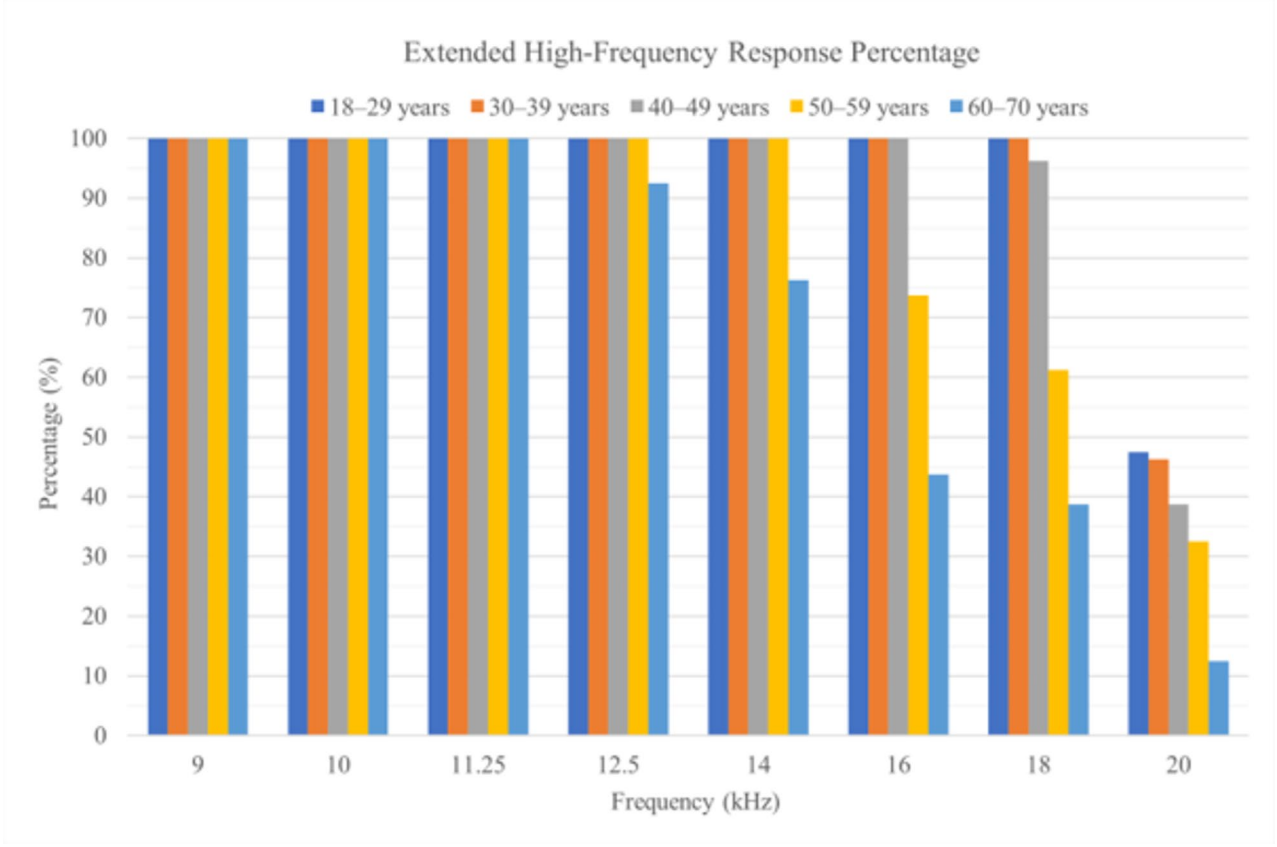

Fig. 2 Extended high-frequency response percentage

lower than those of the 50–59 and 60–70 age groups (all $p < 0.001$). Finally, the 11.25 and 12.5 kHz thresholds of the 50–59 age group were found to be statistically lower than the 60–70 age group (both $p < 0.001$).

The 14 and 16 kHz thresholds of the 18–29 age group were statistically lower than those of the 30–39 age group ($p = 0.002$, $p < 0.001$, respectively). Similarly, the 14 and 16 kHz thresholds of both the 18–29 and 30–39 age groups were statistically lower than those of the 40–49 age group (all $p < 0.001$). Furthermore, the 14 and 16 kHz thresholds of the 18–29, 30–39, and 40–49 age groups were statistically lower than those of the 50–59 and 60–70 age groups (all $p < 0.001$).

The 18 kHz threshold of the 18–29 age group was statistically obtained as lower than that of the 30–39 age group ($p = 0.009$). In addition, the 18 kHz thresholds of the 18–29 and 30–39 age groups were statistically lower than those of the 40–49, 50–59, and 60–70 age groups (all $p < 0.001$). Furthermore, the 20 kHz threshold of the 18–29 age group was obtained at a statistically lower level than those of the 40–49 and 50–59 age groups ($p = 0.022$, $p = 0.031$, respectively). Comparison of EHF thresholds across age groups, excluding the right/left ear and gender factors, are presented in Table 4. The mean EHF threshold curves for the age groups are illustrated in Fig. 3.

The relationship between age and EHF thresholds was assessed using a Pearson correlation test. As shown in the Table 5, the findings revealed a moderate positive correlation between age and all EHF thresholds. The frequency with the highest correlation with age was 12.5 kHz ($r = 0.828$, $p < 0.001$), and the frequency with the lowest correlation was 20 kHz ($r = 0.267$, $p = 0.001$).

Discussion

This study presents normative data on EHF thresholds in a healthy adult population using descriptive and statistical analyses adjusted for ear side, gender, and age factors. Descriptive analyses of pure-tone audiometry results are also included. Similar studies have been reported in the literature. However, they vary in terms of the number of participants, gender, the number of ears, and the audiometric instruments used. Most studies report data in dB SPL due to the lower MOL of EHF audiometry compared to conventional pure-tone audiometry [1, 13, 14, 18–26]. Studies that present EHF thresholds in dB HL, as in our study, are limited. It is emphasized in the literature that dB HL thresholds are advantageous for practical applications in the clinic [12, 29].

The results of conventional pure-tone audiometry are variable in the literature. Wang et al. [12] reported that

Table 2 Comparison of hearing thresholds between the left and right ears in the extended high-frequency range (9–20 kHz) across all age groups

Frequency (kHz)	Ear Side	Hearing thresholds (dB HL) across all age groups M (SD)				
		18–29 years	**30–39 years**	**40–49 years**	**50–59 years**	**60–70 years**
9	Left	5.38 (8.80)	5.38 (7.20)	9.63 (9.83)	25.00 (18.12)	42.13 (18.60)
	Right	4.63 (7.79)	6.50 (10.57)	11.13(10.09)	21.50 (14.15)	40.88 (18.74)
	Analysis	$p=0.688$	$p=0.58$	$p=0.503$	$p=0.339$	$p=0.765$
10	Left	-2.25 (8.00)	0.63 (8.93)	5.75 (11.35)	27.00 (20.37)	44.50 (19.54)
	Right	-0.13 (8.51)	1.63 (10.02)	7.38 (11.43)	23.88 (15.79)	43.00 (19.24)
	Analysis	$p=0.253$	$p=0.639$	$p=0.525$	$p=0.446$	$p=0.73$
11.25	Left	0.63 (6.72)	6.13 (11.79)	10.75 (12.79)	36.88 (24.09)	54.25 (19.20)
	Right	2.00 (8.15)	5.75 (10.23)	13.38 (11.29)	32.75 (21.00)	54.38 (18.68)
	Analysis	$p=0.413$	$p=0.88$	$p=0.333$	$p=0.417$	$p=0.977$
12.5	Left	-4.25 (9.31)	9.13 (13.49)	20.50 (17.90)	47.13 (22.36)	62.03 (16.52)
	Right	-4.13 (8.98)	6.38 (12.04)	21.38 (16.49)	45.63 (21.93)	62.30 (14.70)
	Analysis	$p=0.951$	$p=0.339$	$p=0.821$	$p=0.763$	$p=0.941$
14	Left	2.38 (12.91)	12.88 (19.01)	33.38 (19.26)	54.88 (19.76)	62.33 (11.87)
	Right	1.63 (12.98)	9.75 (15.81)	32.63 (19.08)	52.88 (21.24)	60.81 (14.84)
	Analysis	$p=0.796$	$p=0.427$	$p=0.862$	$p=0.664$	$p=0.659$
16	Left	8.00 (15.22)	26.75 (20.62)	44.50 (11.81)	53.5 (8.00)	53.75 (5.59)
	Right	6.25 (14.71)	23.75 (21.60)	46.75 (11.07)	53.97 (6.32)	55.67 (4.95)
	Analysis	$p=0.603$	$p=0.527$	$p=0.382$	$p=0.806$	$p=0.30$
18	Left	16.50(15.16)	24.75 (14.76)	33.88 (5.60)	36.20 (5.26)	36.76 (3.93)
	Right	18.00(13.29)	24.63 (13.17)	33.78 (4.92)	34.38 (4.50)	36.07 (4.46)
	Analysis	$p=0.639$	$p=0.968$	$p=0.94$	$p=0.199$	$p=0.649$
20	Left	9.05 (7.52)	11.32 (3.67)	13.75 (2.89)	13.57 (2.34)	NA
	Right	10.88 (5.37)	12.22 (4.28)	12.67 (4.17)	12.92 (3.34)	
	Analysis	$p=0.403$	$p=0.493$	$p=0.405$	$p=0.564$	

M: Mean, SD: Standard deviation, kHz: Kilohertz, dB HL: Decibels hearing level, p: Independent samples t-test's p value, NA: Not applicable as response was equal to or less than 20%

hearing thresholds in the 4–8 kHz range were > 25 dB HL by the age of 51. It was stated that this change was due to the natural aging process of the auditory system. As seen in our study, a flat configuration between age groups was observed up to the frequency of 2 kHz, while the thresholds of the 50–59 and 60–70 age groups deteriorated after 4 kHz (see Fig. 1). Our results show that the age-related changes in conventional pure-tone audiometry thresholds are consistent with the literature [1, 12].

An evaluation of the response percentages in the present study revealed a full response across all groups between 125 Hz and 11.25 kHz. However, a decline in the response percentages was observed at 12.5 and 14 kHz for individuals aged ≥ 60, at 16 kHz for those aged ≥ 50, at 18 kHz for those aged ≥ 40, and at 20 kHz for all ages (see Fig. 2). When studies using the dB HL scale were examined, response percentages were lower at many frequencies than in our study. In most studies, responses were obtained up to 16 kHz, and it was stated that these responses were more reliable compared to 18 and 20 kHz [12, 23, 25, 26, 30]. It was reported that the response percentage decreased only at the 20 kHz frequency in the 20–29 age group, dropping to approximately 50% [18, 25]. This finding is consistent with the 47.5% response percentage of the same age group in our study. The 20 kHz threshold in the 60–70 age group was the only variable that exhibited a response percentage below 20% in the present study. These data were excluded from the statistical analyses to avoid disrupting the normalization process. This methodological approach has been adopted in other studies [12, 31]. Valiente et al. [1] reported that a full response should be obtained at frequencies up to 18 kHz for individuals aged < 40 years, up to 14 kHz for those aged 40–49, and up to 11.25 kHz for individuals aged ≥ 50 years. However, our study demonstrated substantially higher response rates extending into the higher frequencies, as illustrated in Fig. 2. The broader preservation of EHF responses observed in our study can be attributed to the strict exclusion criteria implemented in our methodology.

A few studies have been conducted that make comparisons between right and left ear EHF thresholds. The literature has shown that there is no threshold difference between the right and left ears, which is consistent with our study [12, 18, 19, 29]. This finding suggests that the auditory system is symmetrical and integrated in the EHF region. Fausti et al. [21] reported that the presence of asymmetry in EHF thresholds might indicate noise exposure. The symmetrical results confirm the homogeneity of our sample and closely align with the expected profile

Table 3 Comparison of hearing thresholds between males and females in the extended high-frequency range (9–20 kHz) across all age groups

Frequency (kHz)	Gender	Hearing thresholds (dB HL) across all age groups M (SD)				
		18–29 years	30–39 years	40–49 years	50–59 years	60–70 years
9	Male	6.13 (7.72)	4.13 (8.84)	14.25 (9.91)	26.50 (15.78)	43.75 (20.40)
	Female	3.88 (8.73)	7.75 (8.91)	6.50 (8.41)	20.00 (16.25)	39.25 (16.47)
		$p=0.226$	$p=0.72$	$\mathbf{p<0.001}$*	$p=0.073$	$p=0.281$
10	Male	0.25 (7.92)	0.50 (9.92)	10.13 (12.73)	27.00 (18.80)	45.00 (20.94)
	Female	-2.63 (8.47)	1.75 (9.03)	3.00 (8.53)	23.88 (17.63)	42.50 (17.65)
		$p=0.121$	$p=0.557$	$\mathbf{p=0.004}$*	$p=0.446$	$p=0.565$
11.25	Male	0.38 (6.44)	5.50 (12.13)	14.13 (13.95)	36.25 (21.92)	55.88 (18.98)
	Female	2.25 (8.32)	6.38 (9.80)	10.00 (9.54)	33.38 (23.35)	52.75 (18.77)
		$p=0.263$	$p=0.724$	$p=0.127$	$p=0.572$	$p=0.461$
12.5	Male	-2.75 (9.26)	8.75 (13.95)	23.00 (19.11)	48.50 (22.76)	64.86 (13.60)
	Female	-5.63 (8.78)	6.75 (11.58)	18.88 (14.78)	44.25 (21.32)	59.61 (16.94)
		$p=0.158$	$p=0.487$	$p=0.284$	$p=0.391$	$p=0.147$
14	Male	4.13 (12.45)	10.88 (17.90)	33.5 (18.89)	55.25 (19.31)	66.60 (8.98)
	Female	-0.13 (13.08)	11.75 (17.19)	32.50 (19.45)	52.50 (21.60)	58.06 (14.85)
		$p=0.141$	$p=0.824$	$p=0.816$	$p=0.55$	$\mathbf{p=0.013}$*
16	Male	6.63 (14.74)	18.75 (21.15)	45.00 (12.19)	54.48 (6.86)	54.55 (6.11)
	Female	7.63 (15.23)	31.75 (19.03)	46.25 (10.73)	53.00 (7.50)	54.58 (5.09)
		$p=0.766$	$\mathbf{p=0.005}$*	$p=0.628$	$p=0.432$	$p=0.985$
18	Male	17.25 (14.98)	19.38 (15.70)	33.78 (5.45)	35.21 (5.21)	36.82 (2.52)
	Female	17.25 (13.54)	30.00 (9.34)	33.88 (5.13)	35.40 (4.77)	36.25 (4.83)
		$p=1.00$	$\mathbf{p<0.001}$*	$p=0.94$	$p=0.894$	$p=0.720$
20	Male	8.53 (6.32)	10.00 (4.41)	13.08 (4.35)	13.85 (3.00)	NA
	Female	10.95 (6.82)	13.61 (2.30)	13.33 (2.97)	12.69 (2.59)	
		$p=0.268$	$\mathbf{p=0.004}$*	$p=0.846$	$p=0.304$	

M: Mean, SD: Standard deviation, kHz: Kilohertz, dB HL: Decibels hearing level, p: Independent samples t-test's p value, *: Statistically significant relationship ($p<0.05$) between the variables, NA: Not applicable as response was equal to or less than 20%

Table 4 Comparison of extended high-frequency hearing thresholds (9–20 kHz) across age groups

Frequency (kHz)	Hearing thresholds (dB HL) across all age groups M (SD)					*p* value
	18–29 years	30–39 years	40–49 years	50–59 years	60–70 years	
9	5.00 (8.27)	5.94 (9.00)	10.38 (9.93) △▲	23.25 (16.25) △▲◆	41.50 (18.56) △▲◆v	**<0.001***
10	-1.19 (8.28)	1.13 (9.45)	6.56 (11.35) △▲	25.44 (18.18) △▲◆	43.75 (19.28) △▲◆v	**<0.001***
11.25	1.31 (7.45)	5.94 (10.97) △	12.06 (12.06) △▲	34.81 (22.55) △▲◆	54.31 (18.82) △▲◆v	**<0.001***
12.5	-4.19 (9.09)	7.75 (12.78) △	20.94 (17.10) △▲	46.38 (22.02) △▲◆	62.16 (15.53) △▲◆v	**<0.001***
14	2.00 (12.87)	11.31 (17.44) △	33.00 (19.05) △▲	53.88 (20.41) △▲◆	61.56 (13.37) △▲◆	**<0.001***
16	7.13 (14.9)	25.25 (21.03) △	45.63 (11.43) △▲	53.73 (7.17) △▲◆	54.57 (5.34) △▲◆	**<0.001***
18	17.25(14.18)	24.69 (13.90) △	33.83 (5.25) △▲	35.31 (4.94) △▲	36.45 (4.12) △▲	**<0.001***
20	9.87 (6.63)	11.76 (3.95)	13.23 (3.55) λ	13.27 (2.81) λ	NA	**0.015***

M: Mean, SD: Standard deviation, kHz: Kilohertz, dB HL: Decibels hearing level, NA: Not applicable as response was equal to or less than 20%,

△: Statistically significantly different from the 18–29 age group (Games-Howell test, $p<0.05$)

▲: Statistically significantly different from the 30–39 age group (Games-Howell test, $p<0.05$)

◆: Statistically significantly different from the 40–49 age group (Games-Howell test, $p<0.05$)

v: Statistically significantly different from the 50–59 age group (Games-Howell test, $p<0.05$)

λ: Statistically significantly different from the 18–29 age group (Tukey HSD test $p<0.05$)

*: Statistically significant relationship between the groups (One-way ANOVA, $p<0.05$)

of a population without noise exposure or medication use.

Gender analysis were resulted in both similar and different results from the studies. The existing body of literature on this subject is inconclusive, with some studies [24] indicating that males have better EHF thresholds at certain frequencies, while others [32] indicate that females have better EHF thresholds. Other studies have indicated that there is no significant difference in EHF thresholds between the genders [13, 14, 19, 26, 31, 33]. In the present study, females in the 30–39 age group showed worse hearing thresholds at 20 kHz than males;

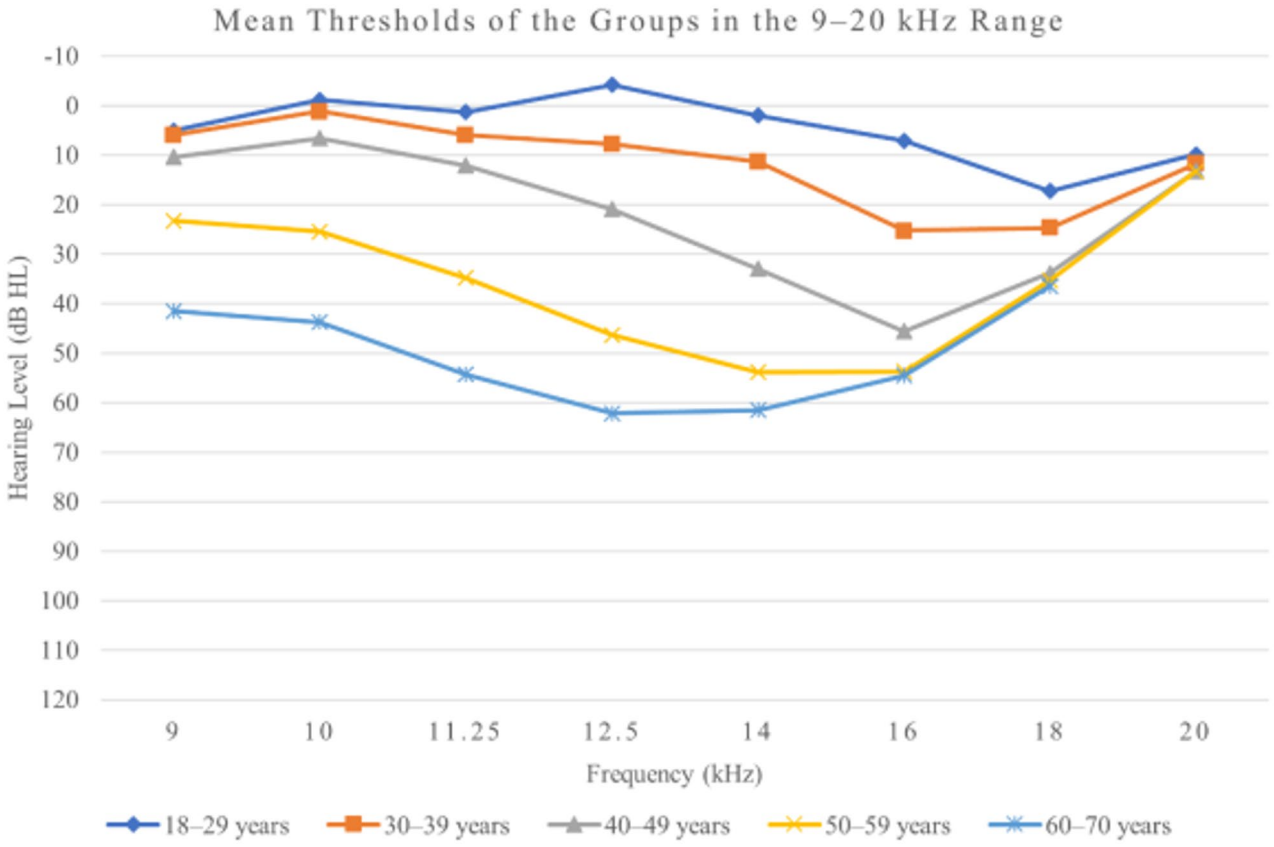

Fig. 3 The mean threshold curves within the 9–20 kHz range for the age groups

Table 5 Correlation between age and extended high-frequency thresholds

Frequency	*r*	*p* value	Frequency	*r*	*p* value
9 kHz	0.702	< 0.001*	14 kHz	0.790	< 0.001*
10 kHz	0.748	< 0.001*	16 kHz	0.774	< 0.001*
11.25 kHz	0.770	< 0.001*	18 kHz	0.570	< 0.001*
12.5 kHz	**0.828**	< 0.001*	20 kHz	**0.267**	0.001*

r: Pearson correlation coefficient, *: Statistically significant relationship between the variables ($p < 0.05$)

in contrast, females in the 60–70 age group demonstrated better thresholds at 14 kHz. This observation may be due to the decrease in the EHF response percentages of the groups. However, statistically significant differences were found at 16 and 18 kHz in the 30–39 age group, and at 9 and 10 kHz in the 40–49 group, despite obtaining high response rates. Lee et al. [13] have suggested that gender differences may be due to ear canal acoustics, attention, or individual variables. In the present study, the observed differences in gender-related thresholds at 9, 10, 16, and 18 kHz are hypothesized to be associated with individual differences consistent with the literature. Rather than reflecting participant attention levels, these isolated frequency differences are more accurately explained by acoustic and anatomical mechanisms. Variations in ear canal resonance can alter the effective sound pressure level reaching the tympanic membrane. Because acoustic interactions are highly dependent on individual ear canal structure and transducer placement, they characteristically manifest as sharp, frequency-specific variations in the EHF range as well-supported by the literature [23, 34]. To provide a clearer context for these gender-related variations, the magnitude of the differences was evaluated using Cohen's standard benchmarks, where effect sizes are classified as small (d = 0.2), medium (d = 0.5), and large (d = 0.8) [35]. In the 30–39 age group, the calculated effect sizes at 16 kHz (d = 0.65), 18 kHz (d = 0.82), and 20 kHz (d = 1.03) indicate medium-to-large differences where females had higher thresholds. Conversely, in the 40–49 age group, males demonstrated significantly higher thresholds with a large effect size at 9 kHz (d = 0.84) and a medium effect size at 10 kHz (d = 0.66). Furthermore, a medium effect size was observed at 14 kHz (d = 0.70) in the 60–70 age group, where males again had higher thresholds. These varying magnitudes across isolated frequencies indicate that the effect of gender moving beyond mere statistical significance is non-uniform.

Prior multivariate analysis studies have demonstrated that age is the primary factor influencing EHF threshold changes [14, 36]. Wang et al. [12] reported that for individuals aged < 30 years, EHF thresholds were < 26 dB HL.

They observed that a decline in EHF thresholds becomes particularly evident after the third decade of life and progresses more rapidly in the fifth and sixth decades. In the present study, statistically significant deterioration in hearing thresholds was observed across all frequencies, particularly among the 40–49 age group, when compared to younger age groups. The 30–39 age group also exhibited deterioration at frequencies ≥ 11.25 kHz. In the 50–59 and 60–70 age groups, thresholds were found to be worse at all frequencies when compared to younger participants. The present study shows that the differences in thresholds between the groups begin in the 30–39 age group, but the differences become more pronounced in the 40s and beyond. However, even in the 18–29 age group, the increased thresholds and reduced response percentages at 20 kHz highlight the effects of EHF in this age group. In line with all these findings, the worsening of thresholds with increasing age in our study is consistent with the literature. As the extant literature emphasizes, age is the most significant factor in EHF thresholds [1, 9, 12, 25, 26, 32, 33, 37–39].

Another perspective in the extant literature is that hearing thresholds deteriorate with increasing frequency [1, 12, 23, 25, 29, 30]. Wang et al. [12] reported a significant difference at all frequencies between 9 and 16 kHz. In contrast, Stelmachowicz et al. [26] found that threshold deterioration was more pronounced between 15 and 18 kHz. In another study, it was stated that thresholds were particularly worsened between 12 and 18 kHz [23]. The findings of these prior studies are consistent with the results of the present study. When correlation analyses were examined, Sakamoto et al. [30] demonstrated that the strongest correlation with age is 14 kHz. In our study, this EHF value was 12.5 kHz. The observed difference may be due to the number of samples and the dB HL scale used.

The literature shows that thresholds deteriorate with increasing frequency. However, the calculated mean thresholds appear artificially better after 18 kHz in the 18–29 and 30–39 age groups, after 16 kHz in the 40–49 age group, after 14 kHz in the 50–59 age group, and after 12.5 kHz in the 60–70 age group. These findings do not reflect an actual clinical superiority in hearing acuity; rather, they represent a statistical artifact. Due to the decrease in response percentages and the technical constraint of MOL at these terminal frequencies, non-responding ears were excluded from the analysis. Consequently, the mean values were calculated exclusively for the ears with preserved responses, leading to an overestimation of the overall cohort's sensitivity. These results are consistent with other studies using dB HL as a scale [12, 26].

A primary technical limitation of the present study is the decrease in the MOL of the audiometer, especially at frequencies ≥ 12.5 kHz. This may result in lower response percentages, particularly at frequencies of 18–20 kHz. Additionally, from a methodological perspective, the relatively small sample size within specific gender and age subgroups ($n = 20$) represents a constraint that may limit the broader generalizability of the findings. Future developments in audiometer technology will undoubtedly contribute to establishing more accurate EHF normative data across diverse populations.

Conclusion

The normative EHF thresholds established in this study provide a reliable baseline dataset; such reference data are essential for future clinical screening to identify early EHF hearing loss. It is anticipated that these data, determined according to five age groups, will make an important contribution to the evaluations made at dB HL level in clinics. The evaluations revealed no statistically significant differences between right and left ear thresholds. In the gender-based analysis, threshold differences observed at certain frequencies are thought to be influenced by individual factors such as response percentage, ear canal resonance or transducer placement. Generally, hearing thresholds increase, and EHF response percentages decrease with increasing age and frequency. In accordance with the findings of our study, we conclude that audiologic follow-up to 20 kHz is clinically significant. Our detailed age-group analysis demonstrates a distinct statistical shift, showing that EHF threshold increases become significantly more pronounced from the age of 40 onward. Based on these findings, we recommend more frequent and targeted EHF evaluations for individuals aged ≥ 40 years to detect early-onset age-related auditory changes.

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Author contributions

OFS: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft. AC: Conceptualization, Methodology, Project administration, Resources, Software, Supervision, Validation, Writing – review & editing.

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Data availability

The data sets used for this study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

All procedures performed in this study (date: 08/01/2021- protocol no: 09.2021.76) were carried out in accordance with the ethical standards of the Marmara University institutional and/or national research committee (Clinical

Research Ethics Committee) determined by the 1964 Helsinki Declaration and its later amendments and a signed informed consent form was obtained from all participants.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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