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Original Article

Effect of Age on Distortion Product Otoacoustic Emissions at Extended High Frequencies

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BACKGROUND: The inner ear is most susceptible to the aging effects. Distortion product otoacoustic emissions (DPOAEs) are a good indicator for interpreting the age effects but are usually recorded at up to 8000 Hz frequencies in routine audiologic testing. The present study was designed to assess and compare the DPOAEs at conventional frequencies and at extended high frequencies (EHFs) across different age groups.

METHODS: Extended high-frequency audiometry (9000-16 000 Hz) and DPOAEs from 500-16 000 Hz were recorded on 80 adult (160 ears) participants (15-55 years) with normal hearing sensitivity. The participants were categorized into 4 groups: group I (15-<25 years), group II (25-<35 years), group III (35-<45 years), and group IV (45-55 years).

RESULTS: A statistically significant reduction in EHF thresholds was observed from group III onward. However, the thresholds were comparatively better for group III at frequencies 9000, 10 000, and 11 500Hz than group IV. No significant difference was observed for EHF DPOAEs in groups I and II (except at 16 000 Hz) and III and IV. Distortion product otoacoustic emissions at conventional frequencies in group IV were significantly poorer than the other 3 groups. A weak negative correlation was observed between the DPOAE parameters and EHF thresholds. The effect of age was more pronounced on EHF DPOAEs than EHF thresholds for frequencies 9000, 10 000, and 11 500 Hz.

CONCLUSION: Distortion product otoacoustic emissions at EHF started deteriorating below the age of 30 years and showed a rapid decline above 35 years. Extended high-frequency DPOAEs can be used as screening tools to assess the function of the basal part of the cochlea.

KEYWORDS: Age-induced hearing loss, otoacoustic emissions, hearing impairment, presbycusis

INTRODUCTION

Otoacoustic emissions (OAEs) are the echoes produced by the cochlea.[1] The generation of OAEs is a hallmark of inner ear health and the non-linearity of outer hair cells (OHCs).[2] The diagnostic importance of OAEs has been explained as a non-invasive objective measure used to forecast hearing status when a behavioral audiogram cannot be easily obtained.[3] Among the evoked OAEs, distortion product OAEs (DPOAEs) are always produced when a mechanical non-linearity is found in all normal-hearing individuals.[2] Additionally, it has been shown that decreased DPOAE levels correlate with OHC destruction, which is supported by histological findings and demonstrates that OHCs contribute to the production of DPOAEs.[4] In humans, most DPOAE studies have used conventional frequencies (≤ 8 kHz); however, hearing at extended high frequencies (EHF) is most susceptible to cochlear damage. The origin of both DPOAEs at EHF and conventional frequencies is via a similar biological mechanism in the inner ear.[5] Due to the emergence of EHF DPOAEs in the range of 9000 to 16 000 Hz frequencies, changes in hearing preceding hearing loss in conventional audiometric frequencies (250 to 8000 Hz) could be detected in the initial stages.[5,6]

Age-related changes are significantly associated with lower DPOAE amplitude.[7] Age-related hearing loss starts from basal frequencies and then progresses to apical ones. Distortion product otoacoustic emission values determine cochlear health as a function of frequency.[8] Reduction in hearing sensitivity at EHF may signify preclinical hair cell loss in the conventional frequencies.[9] A reduction in the amplitude of DPOAEs reported with aging is significantly seen even before any change is observed in pure tone audiometry.[10] EHF DPOAEs are essential in identifying ototoxicity and noise-induced hearing loss.[11] The hearing thresholds at EHF begin

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to deteriorate from 35 years onward; initially, the effects are more observed in the high frequencies (14 &16 kHz), and as age increases, the deterioration spreads to low frequencies. The increase in hearing threshold rate is more rapid in males than females.[12]

On the other hand, it is still being determined if age-related hearing loss has a similar impact on the DPOAEs at EHFs. Therefore, further research is required to understand how aging affects DPOAEs at conventional and EHFs. Understanding the effect of age on DPOAEs at EHFs could help identify individuals at greater risk of developing hearing impairment. It could further guide in counseling and follow-up assessments. Hence, the present study is designed to assess the effect of age-related hearing loss on DPOAEs at EHF.

METHODS

Participants

The study was conducted on 80 adult (160 ears) participants aged 15-55 years, with an equal number of males and females. The participants were further categorized into 4 subgroups to observe age-related changes. The mean age and standard deviation of male and female participants of 4 groups are as follows: group I (15-<25 years) 21.4 (2.19) and 20.7 (2.34), group II (25-<35 years) 29.4 (2.10) and 29.9 (2.27), group III (35-<45 years) 40.5 (4.38) and 39.7 (2.76), and group IV (45-55 years) 50.6 (3.69) and 49.3 (2.48). The inclusion criteria for the selected participants were normal otoscopic and audiometric findings with no associated medical, neurological, or otological history.

Procedure

Case History and Otoscopic Evaluation

A detailed case history was obtained from all the subjects to rule out any pathological conditions of the auditory system, noise exposure, and associated medical or neurological history. A visual examination of the external auditory meatus and the eardrum was performed using a handheld otoscope to rule out the presence of wax, foreign bodies in the ear canal, or external or middle ear pathologies.

Pure Tone Audiometry

A dual-channel calibrated GSI Audiostar Pro (Grason-Stadler, Eden Prairie, Minnesota, USA) audiometer was used to estimate the hearing thresholds in dB HL using the modified Hughson and Westlake procedure.[13] For all the participants, TDH 39 headphones were used to obtain the air conduction thresholds at octave frequencies from 250 to 8000 Hz. A B-71 bone vibrator was used to measure bone conduction thresholds at 250 to 4000 Hz octave frequencies. The participants were instructed to raise their fingers whenever they heard a sound. The mean and SD of hearing thresholds across 4 age groups are shown in Figure 1.

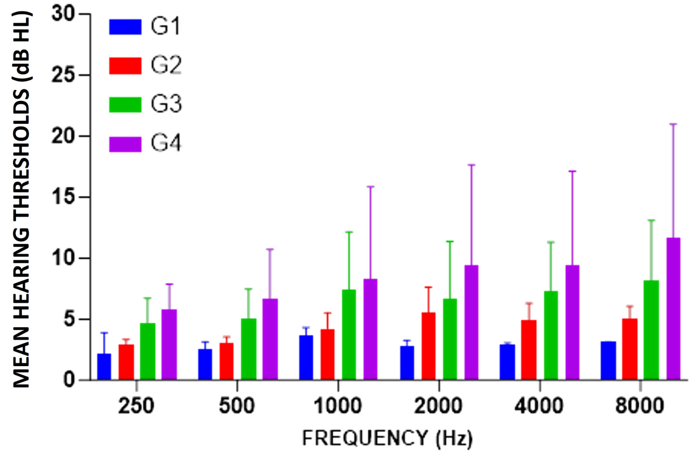

Figure 1. Mean and SD of air conduction thresholds (dB HL) at conventional frequencies across age groups.

Extended High-Frequency Audiometry

A dual-channel calibrated GSI Audiostar Pro (Grason-Stadler, Eden Prairie, Minnesota, USA) audiometer was used to estimate the extended high-frequency (EHF) thresholds in dB SPL using the modified Hughson-Westlake procedure for all the subjects.[13] Sennheiser HDA-200 headphones were used to measure the thresholds at 9000, 10 000, 11 250, 12 500, 14 000, and 16 000 Hz for both ears. The participants were instructed to respond similarly to pure tone audiometry at conventional frequencies.

Distortion Product Otoacoustic Emission Recording

Distortion product otoacoustic emission measurements were carried out using a calibrated Hear ID 5.1 (Mimosa Acoustics, Inc., Champaign, IL, USA) OAEs system in a sound-treated room. After ensuring an appropriate probe fitting, in-ear calibration was performed prior to recording both the conventional and EHF DPOAEs. The instrument provided a chirp stimulus via transducers for in-the-ear calibration. The 2 calibration curves overlapping were required to ensure proper probe fit. If the reproducibility of the 2 curves was below 95 percent, the test was aborted and the probe was refitted. In the current study, 95% or more reproducibility was considered for all the DPOAE measurements. Distortion product otoacoustic emission recording was carried out using 2 frequencies, f1 (lower frequency) and f2 (higher frequency), and 2 intensities, L1 (65 dB SPL) and L2 (55 dB SPL). In humans, the most common distortion product ear occurs at 2f1-f2 with an f2/f1 ratio of 1.22. The DPOAE measurements at 12 f2 frequencies, which include 500, 1000, 1500, 2000, 4000, 6000, 8000, 9000, 10 250, 12 500, 14 000, and 16 000 Hz, were carried out for both ears.

The participants were informed about the test procedure and instructed to relax, minimize body movements and not to speak while recording the DPOAEs. The measurements were taken twice, and the average of both was considered. All DPOAE recordings were

MAIN POINTS

- Age-related hearing loss significantly affects the distortion product otoacoustic emissions at extended high frequencies.
- Significantly higher distortion product otoacoustic emission at extended high frequencies for participants less than 35 years compared to participants greater than 35 years of age.
- Distortion product otoacoustic emission at extended high frequencies starts deteriorating at the age of 30 years and shows a rapid decline beyond 35 years.
- Deterioration of distortion product otoacoustic emission at extended high frequencies is observed before showing damage in the conventional audiometric frequencies.

Table 1. Mean, Median, SD, and Interquartile Range (IQR) of Participants Across 4 Groups

Groups	Age Range (Years)	Number of Subjects		Mean Age (SD)		Median (IQR)	
		Male	Female	Male	Female	Male	Female
Group I	15-<25	10	10	21.4 (2.19)	20.7 (2.34)	21.7 (3.73)	20.6 (4.07)
Group II	25-<35	10	10	29.4 (2.10)	29.9 (2.27)	29.4 (3.98)	29.8 (3.32)
Group III	35-<45	10	10	40.5 (4.38)	39.7 (2.76)	39.6 (5.80)	39.4 (4.95)
Group IV	45-55	10	10	50.6 (3.69)	49.3 (2.48)	49.9 (7.49)	49.5 (5.13)

IQR, interquartile range.

analyzed using standard OAE parameters like OAE amplitude and signal-to-noise ratios (SNRs). The response levels were expressed in dB SPL, and the SNRs were calculated as the difference between the DPOAE level and noise floor in dB SPL.

Ethical Consideration

The ethics committee approval for bio-behavioral research projects involving human subjects at the All India Institute of Speech and Hearing (AIISH), Mysuru, India, approved the present study protocol on February 2, 2023. The test procedures followed in the present study are non-invasive. Before evaluation, the participants were informed about the study's methods and goals, and informed consent was obtained.

RESULTS

The present study investigated the effect of age on extended high-frequency DPOAEs in adults aged 15-55. The study was conducted on 80 adults (160 ears) with an equal number of male and female participants, and they were further divided into 4 groups based on age. No significant difference in age was observed between the male and female participants across the 4 age groups ($P > .05$). The mean, median, SD, and interquartile range (IQR) of the participants across different age groups are depicted in Table 1. The DPOAE amplitude and SNR were compared across the 4 groups as part of the between-group analysis. The relationship between pure tone thresholds, DPOAEs amplitude, and SNR was compared via within-group analysis.

Statistical Package for the Social Science (SPSS) version 26 software was used for descriptive and quantitative data analysis. The normality of data distribution was assessed using the Shapiro–Wilk test. Descriptive statistics were conducted to obtain the median and interquartile range for various parameters of EHF DPOAEs and EHF thresholds. The results of the Shapiro–Wilk test showed that the data were not normally distributed ($P < .05$). Hence, non-parametric inferential statistics were administered to the data. Between-group comparisons were made using the Kruskal–Wallis test to study the effect of age on DPOAEs' amplitude, SNR, EHF thresholds, and gender across the 4 groups. A pairwise comparison across all age groups shows which groups differ significantly in DPOAE amplitude, SNR, and EHF thresholds. A correlation analysis was conducted using Spearman's rho coefficient to see the relationship between the EHF PTA and the DPOAEs' amplitude.

Noise Floor

The Kruskal–Wallis test was used to determine whether age had an effect on the DPOAEs' noise floor across 4 groups. The results showed no significant difference ($\chi^2(3) = 4.69$, $P = .83$) at all conventional frequencies from 500 to 8000 Hz and EHF from 9000 to 16 000 Hz across the 4 groups ($P > .05$).

Distortion Product Otoacoustic Emission Amplitude and Signal-to-Noise Ratio at Extended High Frequencies

The DPOAE amplitude for EHF lies within the range of −32 to 17 dB SPL and SNR within −30 to 23 dB across frequencies. The Kruskal–Wallis test showed a significant difference across all the extended high frequencies (9000 to 16 000 Hz) for DPOAE amplitude ($\chi^2(3) = 78.19$, $P < .001$) and SNR ($\chi^2(3) = 79.32$, $P < .001$). The results depicted decreased DPOAE amplitude and SNR across frequencies with increased age (Figure 2).

A pairwise comparison was done to see which group differed significantly from the others. For extended high frequencies (9000-16 000 Hz), there was no significant difference in DPOAE amplitude and SNR between groups I and II (except at 16 000 Hz) and groups III and IV (except at 9000 Hz) ($P > .05$). However, group I and group II differed significantly from group III and group IV for DPOAE amplitude and

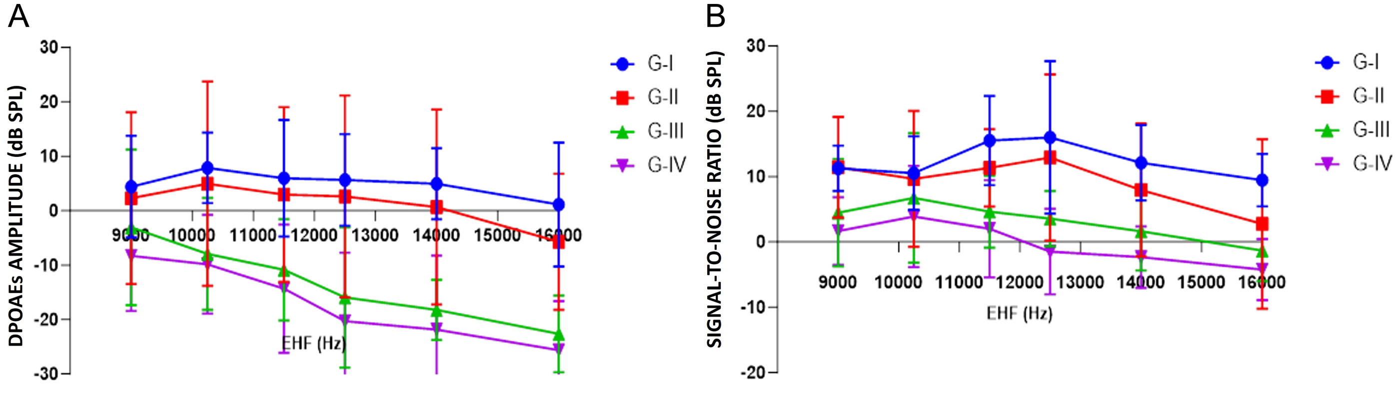

Figure 2. The median and interquartile range for DPOAEs A. Amplitude, B. SNR at EHF across different age groups.

Table 2. Pairwise Comparison for DPOAE Amplitude at EHF Across the 4 Age Groups

Frequency (Hz)	G-I vs G-II		G-I vs G-III		G-I vs G-IV		G-II vs G-III		G-II vs G-IV		G- III vs G- IV	
	Test Statistics	P	Test Statistics	P	Test Statistics	P	Test Statistics	P	Test Statistics	P	Test Statistics	P
9000	.407	.684	3.375	.001*	6.639	.000*	2.968	.003*	6.232	.000*	3.264	.001*
10 250	1.598	.062	3.623	.000*	4.014	.000*	2.025	.004*	1.416	.002*	.391	.696
11 500	0.640	.080	6.102	.000*	8.493	.000*	3.462	.000*	5.853	.000*	1.85	.067
12 500	.697	.486	6.012	.000*	7.740	.000*	5.315	.000*	7.043	.000*	1.928	.084
14 000	1.734	.083	6.318	.000*	8.609	.000*	4.584	.000*	6.875	.000*	.291	.052
16 000	4.778	.000*	6.087	.000*	8.503	.000*	1.309	.190	3.725	.000*	1.416	.096

Group I, 15-<25 years; group II, 25-<35 years; group III, 35-<45 years; group IV, 45-55 years; * $P < .05$ (significance difference).

SNR in all the test frequencies ($P < .05$). The results of the pairwise comparisons are shown in Tables 2 and 3.

Distortion Product Otoacoustic Emission Amplitude and Signal-to-Noise Ratio at Conventional Frequencies

The DPOAE amplitude for CF lies within the range of −15 to 30 and SNR within −8 to 34 SPL. The Kruskal–Wallis test showed a significant difference across all the conventional frequencies (500-8000 Hz) for DPOAE Amplitude ($\chi^2(3)=47.83$, $P < .001$) and SNR ($\chi^2(3)=69.34$, $P < .001$). The results depicted decreased DPOAE amplitude and SNR across frequencies with increased age (Figure 3).

A pairwise comparison was done to see which group differed significantly from the others. For conventional frequencies (500-8000 Hz), the data analysis showed no significant difference between groups I and II ($P > .05$) for the DPOAE parameters. Group III differed significantly from group I and group II (except at 500, 1000, and 1500 Hz) for DPOAE amplitude and SNR. Similarly, group IV differed significantly from other groups for DPOAE amplitude and SNR ($P < .05$). Except for frequencies 500, 1000, and 1500 Hz, group IV and group III showed no significant difference ($P > .05$). The results of the pairwise comparison of DPOAE amplitude and SNR are shown in Tables 4 and 5, respectively.

Extended High-frequency Audiometry

The hearing thresholds at extended high frequencies were compared in different age groups (Figure 4), and the results showed a significant difference at all frequencies from 9000 to 16 000 Hz ($P < .05$). The hearing thresholds were better at 9000 for all the groups and worsened across frequencies as the age increased, with no responses in group III (35-<45 years) and Group IV (45-55 years) participants at 16 000 Hz.

The EHF thresholds lie within the 20-95 dB SPL range across 4 age groups. The Kruskal–Wallis test showed that EHF hearing thresholds (9000-16000 Hz) were significantly different across 4 age groups ($P < .05$). Therefore, pairwise comparisons were conducted to see which group differed significantly from the other groups. The data analysis showed that groups I and II significantly differed from groups III and IV ($P < .05$). There was no significant difference ($P > .05$) between group I (15-<25 years) and group II (25-<35 years) except at the 16 000 Hz frequency. The last 2 groups, group III (35-<45 years) and group IV (45-55 years), also showed no significant difference across frequencies except at 9000, 10 000, and 11 500 Hz frequency ($P > .05$) since the thresholds at 12 500, 14 000, and 16 000 Hz reached near the maximum limits of the audiometer. The details of the pairwise comparison are shown in Table 6.

Gender Effect Across Age Groups

The present study reported a gender effect on the EHF thresholds across the 4 age groups. There was a significant effect of gender at 9000 Hz in groups II to group IV ($P < .05$). A significant difference was observed for EHF DPOAE parameters at all frequencies except 16 000 Hz in all groups, 12 500 Hz in groups II and III, and 11 500 Hz in group IV ($P < .05$). Similarly, for conventional DPOAEs, a significant effect of gender was observed at frequencies 2000 and 8000 Hz in groups I and IV, and 8000 Hz in group II.

Correlational Analysis

Extended High-Frequency Pure Tone Audiometry and Distortion Product Otoacoustic Emission Amplitude

Spearman's rho (ρ) coefficient was computed to assess the relationship between extended high-frequency hearing thresholds and DPOAE amplitude. The correlation analysis was carried out by excluding the hearing thresholds of the 16 000 Hz frequency for group IV, as only 3 out of 20 participants showed a response. The results showed

Table 3. Pairwise Comparison for DPOAEs SNR at EHF Across the 4 Age Groups

Frequency (Hz)	G-I vs G-II		G-I vs G-III		G-I vs G-IV		G-II vs G-III		G-II vs G-IV		G-III vs G-IV	
	Test Statistics	P	Test Statistics	P	Test Statistics	P	Test Statistics	P	Test Statistics	P	Test Statistics	P
9000	.730	1.00	4.874	.001*	7.269	.000*	4.117	.000*	6.536	.000*	2.419	.016*
10 250	.895	.215	2.130	.000*	5.275	.000*	2.650	.001*	7.713	.005*	2.063	.098
11 500	2.196	.169	5.703	.000*	7.926	.000*	3.507	.000*	5.730	.000*	2.222	.270
12 500	1.984	.086	6.721	.000*	8.765	.000*	4.735	.000*	6.779	.000*	2.044	.401
14 000	.653	.301	7.054	.000*	8.961	.000*	4.400	.000*	6.308	.000*	1.908	.056
16 000	4.744	.000*	6.768	.000*	9.063	.000*	1.023	.002*	4.318	.000*	2.295	.26

Group I, 15-<25 years; group II, 25-<35 years; group III, 35-<45 years; group IV, 45-55 years; SNR, signal-to-noise ratio. * $P < .05$ (significance difference).

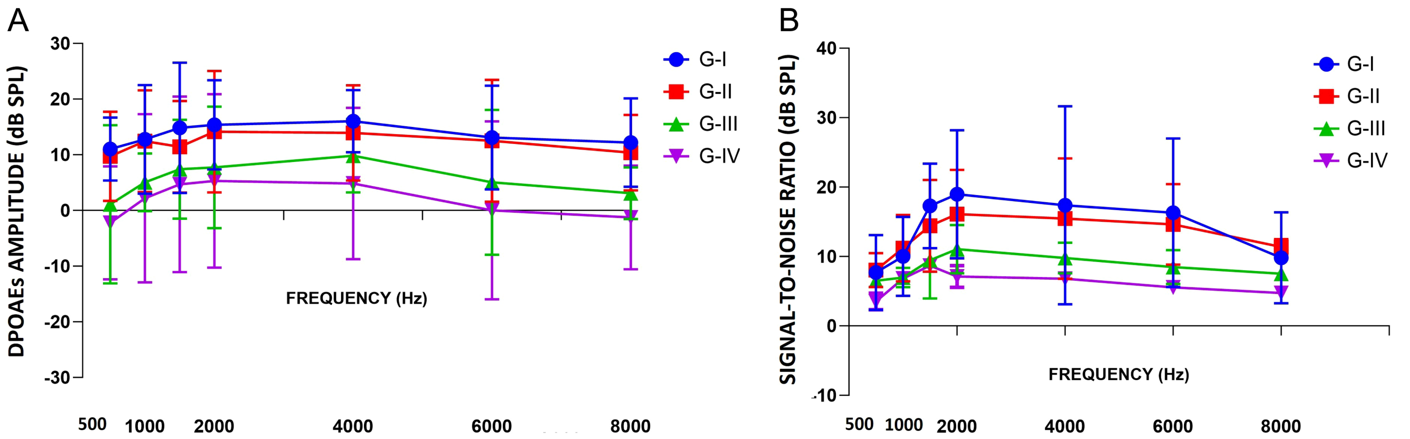

Figure 3. The median and interquartile range for DPOAEs A. Amplitude, B. SNR at conventional frequencies across different age groups.

a weak negative correlation between the 2 variables across age groups (ρ (158) = −0.26).

Extended High-Frequency Pure Tone Audiometry and Conventional Frequency Distortion Product Otoacoustic Emission Amplitude

Correlation statistics were conducted to see the relationship between EHF PTA and DPOAE parameters at conventional frequencies (500-8000 Hz). The results implied a weak negative correlation between DPOAE amplitude and EHF PTA, ρ (158) = −0.07, with exceptions observed for group III at 1500 Hz for all the EHFs, where a weak negative correlation was seen.

DISCUSSION

The present study aimed to investigate the effect of age-related hearing loss on DPOAEs at EHF across 4 groups ranging between 15 and 55 years. The results obtained in the present study are discussed below.

Effect of Age on Extended High Frequency Pure Tone Thresholds

Much literature has reported that hearing tends to deteriorate with age, and the effect is observed more on high frequencies than on low frequencies.[14,15] The histopathological data of human temporal bone also revealed a substantial age-related reduction of outer and inner hair cells, particularly in the cochlear base.[16,17]

The present study measured EHF hearing thresholds (9000, 10 000, 11 500, 12 500, 14 000, and 16 000 Hz) for 4 different age groups. This study showed a significant deterioration in hearing thresholds from group III (35-< 45 years) in all EHFs, with no response at 16 000 Hz, compared to groups I and II. The worst thresholds were observed for group IV, aged 45-55, with no responses at 14 000 and 16 000 Hz. However, even for group II (25-<35), the thresholds were slightly higher at 16 000 Hz than group I.

The study's findings are similar to those previously reported in the literature, which measured EHF thresholds for participants aged 21-70 years.[18] The authors reported that subjects below 30 years have responses up to 16 000 Hz. Extended high-frequency thresholds deteriorate from 35 years onward and worsen above 50 years, with no responses for frequencies above 14 000 Hz. A study that measured both conventional and EHF thresholds concluded that EHF thresholds decline as a function of age from 30 years onward for frequencies above 16 000 Hz.[19] As the age increases, the ability to respond to EHF decreases, and the decline is observed more from 35 years onwards.[12]

Two separate aging processes exist, operating on 2 different time scales: slow and rapid.[20] The slow process is primarily active for the lower frequencies below 8000 Hz. Hence, the decline in hearing thresholds is not observed during early aging for conventional frequencies. On the other hand, the rapid process is primarily active for frequencies beyond 11 000 Hz and in subjects aged 30 years. This phenomenon explains why aging results in the progressive degeneration of hair cells in the cochlea at EHF. Another reason for reduced hearing sensitivity at EHFs with aging is devascularisation associated with atrophy and acellularity of the spiral ligament and stria vascularis. This devascularization leads to the thickening of the

Table 4. Pairwise Comparison of DPOAE Amplitude at Conventional Frequencies Across the 4 Age Groups

Frequency (Hz)	G-I vs G-II		G-I vs G-III		G-I vs G-IV		G-II vs G-III		G-II vs G-IV		G-III vs GIV	
	Test Statistics	*P*	Test Statistics	*P*	Test Statistics	*P*	Test Statistics	*P*	Test Statistics	*P*	Test Statistics	*P*
500	3.790	.790	4.307	.002*	5.836	.000*	0.518	.605	2.046	0.41	1.529	0.126
1000	−.463	.786	−.735	.002*	4.646	.000*	−.271	.053	4.183	.000*	3.912	.201
1500	.321	.748	2.136	.003*	6.559	.000*	1.815	.050	6.238	.000*	4.423	.090
2000	2.558	.061	3.511	.042*	6.479	.000*	−.953	.040*	3.921	.000*	2.968	.003*
4000	1.999	.056	2.592	.007*	7.185	.000*	.592	.001*	5.186	.000*	4.593	.000*
8000	3.489	.097	5.126	.003*	8.142	.000*	1.636	.002*	4.653	.000*	3.016	.000*

Group I, 15-<25 years; group II, 25-<35 years, group III, 35-<45 years; group IV, 45-55 years. * *P* < .05 (significance difference).

Table 5. Pairwise comparison for DPOAEs SNR at Conventional Frequencies Across the 4 Age Groups

Frequency (Hz)	G-I vs G-II		G-I vs G-III		G-I vs G-IV		G-II vs G-III		G-II vs G-IV		G-III vs G-IV	
	Test Statistics	*P*	Test Statistics	*P*	Test Statistics	*P*	Test Statistics	*P*	Test Statistics	*P*	Test Statistics	*P*
500	2.859	.124	4.603	.000*	7.508	.000*	.744	.457	3.650	.000*	2.905	.094
1000	1.149	.251	−1.258	.020*	6.208	.000*	−.110	.913	5.059	.000*	4.949	.067
1500	.835	.404	3.728	.000*	7.165	.000*	2.893	.074	6.330	.000*	3.436	.079
2000	2.869	.148	3.868	.000*	7.867	.000*	.999	.009	4.998	.000*	3.999	.000*
4000	2.096	.086	5.543	.000*	9.224	.000*	1.447	.001	7.128	.000*	3.681	.000*
8000	2.922	.130	6.402	.000*	9.093	.000*	3.480	.001	6.170	.000*	2.691	.007*

Group I, 15-<25 years; group II, 25-<35 years; group III, 35-<45 years; group IV, 45-55 years; SNR, signal-to-noise ratio. * *P*< .05 (significance difference).

walls of the associated structures, mainly at the extreme basal end of the cochlea.[21,22] Several authors reported that reduced endo cochlear potential affects the inner ear's sensory structures and alters the supporting structures' physiology. Due to this, oxidative stress is caused, affecting the mitochondrial membrane proteins and disturbing calcium homeostasis, which, in turn, accelerates the rapid process of deteriorating hearing at EHF.[23-25]

In summary, the results of the present study indicate that EHF thresholds start deteriorating from 35 years onward (group III), with no responses in group IV (45-55 years) for frequencies above 14 000 Hz. However, the decline at 16 000 Hz was also observed in group II (25-<35).

Effect of Age-Related Hearing Loss on Extended High-Frequency Distortion Product Otoacoustic Emission Parameters

Enough literature shows that the DPOAEs decline with age due to the loss of compressive non-linearity of the cochlea, hair cells, and spiral ganglion for conventional frequencies between 6000 and 8000 Hz.[7,16,26] The present study showed the significant effect of age on EHF DPOAEs. There was a significant difference between age groups in EHF DPOAE parameters (amplitude and SNR). There was no observed significant difference in DPOAE parameters for group I and group II (except at 16 000 Hz) and group III and group IV (except at 9000 Hz). However, group I and group II differed significantly from group III and group IV regarding DPOAE amplitude and SNR.

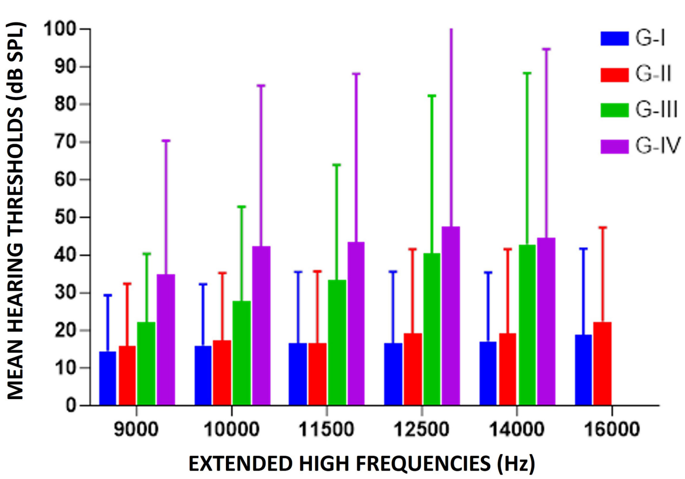

Figure 4. The median and interquartile range of EHF hearing thresholds in dB SPL across 4 age groups.

In humans, most DPOAE studies have used conventional frequencies (≤ 8 kHz); however, hearing at EHFs is most susceptible to cochlear damage. Several authors have reported the effect of age at conventional frequencies for DPOAE parameters.[7,27-29] The changes in compressive non-linearity of the cochlea show reduced amplitude in the middle-aged group (mean age 52) for conventional DPOAEs.[30] Uchida et al[6] reported a deterioration in DPOAE amplitude with age-related hearing loss independent of hearing sensitivity. It has also been reported that the decline of DPOAE amplitude in conventional frequencies begins around 40 years before any observed changes in hearing thresholds.[26]

Aziz et al[14] reported that the sensitivity and specificity of EHF DPOAEs in detecting high-frequency presbycusis were 72.3% and 49.3%, respectively. Studies have also reported good repeatability of EHF DPOAEs to provide preclinical information regarding disorders like ototoxicity and noise induced hearing loss (NIHL).[5,6,31] However, limited studies have been conducted to show the effect of age on EHF DPOAEs.

The present study's findings showed that the deterioration in DPOAE parameters started as early as 35 years. However, a statistically significant decline at extremely high frequencies (16 000 Hz) was also observed for group II (25-<35).

The present study reported a gender effect on the EHF threshold across the age groups. There was a significant effect of gender at 9000 Hz in groups II to group IV (*P* < .05). A significant difference was observed for EHF DPOAE parameters at all frequencies except 16 000 Hz in all groups, 12 500 Hz in groups II and III, and 11 500 Hz in group IV (*P* < .05). Similarly, for conventional DPOAEs, a significant effect of gender was observed at frequencies 2000 and 8000 Hz in groups I and IV, and 8000 Hz in group II. According to Lee et al,[20] the gender effect was observed on pure tone thresholds at EHF. Distortion product otoacoustic emissions at conventional and extended high frequencies could be due to the differences in the ear canal length and volume in males and females, which could have led to such differences.

Relationship Between Extended High-Frequency Pure Tone Thresholds and Distortion Product Otoacoustic Emissions at Conventional and EHF

The present study showed a weak negative correlation between EHF thresholds and DPOAE parameters for conventional and EHF. A similar finding was reported by Schmuziger et al[32] The authors

Table 6. Pairwise Comparison of Extended High Frequencies Hearing Thresholds Across 4 Age Groups

Frequency (Hz)	G-I vs G-II		G-I vs G-III		G-I vs G-IV		G-II vs G-III		G-II vs G-IV		G-III vs G-IV	
	Test Statistics	*P*	Test Statistics	*P*	Test Statistics	*P*	Test Statistics	*P*	Test Statistics	*Ps*	Test Statistics	9000
−1.299	.194	−5.680	.000*	−9.802	.000*	−4.381	.000*	−8.503	.000*	−4.122	.000*	10 000
−1.449	.174	−6.195	.000*	−10.003	.000*	−4.747	.000*	−8.555	.000*	−3.808	.080	11 500
−1.415	.157	−6.438	.000*	−10.127	.000*	−5.023	.000*	−5.023	.000*	−1.689	.506	12 500
−1.941	.052	−7.162	.000*	−10.031	.000*	−5.222	.000*	−8.186	.000*	−3.221	.091	14 000
−3.141	.077	−8.459	.000*	−8.587	.000*	−5.338	.000*	−6.161	.000*	−2.005	.075	16 000
−4.254	.000*	−9.322	.000*	–	–	−5.311	.000*	–	–	–	–	

Group I, 15-<25 years; group II, 25-<35 years; group III, 35-<45 years; group IV, 45-55 years. * *P*<.05 (significance difference).

reported a weak negative correlation between EHF PTA and conventional DPOAEs. This weak negative correlation was due to the level of the primary tones used in the study for DPOAE recording (65/55). Because of this level, the sensitivity of the basal region increases for potential minor pathologies and further increases the strength of the association between high-frequency thresholds and DPOAEs. Hunter et al[33] studied by compiling different findings on EHFs and reported a low correlation between DPOAEs and EHF thresholds. The authors stated that age-related changes in the cochlea alter DPOAE levels before their manifestation in hearing threshold changes.

Most studies compared EHF pure tone thresholds and DPOAEs at conventional and extended high frequencies for the normal and disordered population. According to Reavis et al,[34] the EHF audiometry is more precise in identifying disorders associated with high-frequency hearing loss than conventional DPOAEs. A similar finding was reported by Maccà et al[19] In a study by Arnold et al[35] reported the influence of EHF audiometry on conventional DPOAEs, poorer EHF hearing thresholds showed a decline in conventional DPOAEs at frequencies 6000 and 8000 Hz.

Poling et al[8] measured the EHF thresholds and the EHF DPOAEs. The authors concluded that EHF DPOAEs are a good tool for diagnosing early aging hearing loss, and the strength increases when combined with EHF audiometry. Combining both EHF audiometry and EHF DPOAEs helps us evaluate the cochlear base, specifically preneural peripheral function.[8,14] The authors further concluded that EHF DPOAEs can be a good screening tool with a confirmation via EHF audiometry. The effect of age-related hearing loss is more pronounced in EHF DPOAEs, followed by EHF audiometry.[9] The present study reported a weak negative relationship between EHF thresholds and DPOAE parameters at conventional and EHF.

The results of the present study suggest that the effect of age-related hearing loss is similar for EHF DPOAEs and EHF thresholds. Both start deteriorating from group II (25-< 35 years) at 16 000 Hz. However, the deterioration was observed more from group III (35-<45 years) onward, with no responses at 16 000 Hz. A significant decline for group IV was seen from 14 000 Hz with no response at 16 000 Hz. Also, the thresholds for group III were comparatively better at 9000, 10 000, and 11 500 Hz than group IV, while there was equal deterioration for DPOAE parameters for both groups. There is a weak negative correlation between EHF thresholds and DPOAE parameters. Also, there exists a gender effect for EHF thresholds and DPOAE parameters at EHF and CF across age groups.

To conclude, the deterioration in EHF thresholds starts from 16 000 Hz (25-<35 years), followed by 14 000 Hz (35-<45) and worse above 45 years of age. The DPOAE amplitude and SNR were better for group I > II> III and group IV, being almost similar to group III. The findings suggest that EHF DPOAEs can be a good tool for assessing age-related hearing loss and for early diagnosis of the disorders affecting the basal region of the cochlea. EHF DPOAEs can be a good screening tool as it is less time-consuming, and the findings can be further confirmed with EHF audiometry. Extended high-frequency DPOAEs can predict basal part damage of the cochlea way before the conventional DPOAEs. Follow-ups will be earlier and can further help in early management.

CONCLUSION

The findings of the present study suggest that age-related hearing loss significantly affects the DPOAEs at extended high frequencies. The deterioration can be seen before any change appears in the standard frequencies. The DPOAEs at extended high frequencies start deteriorating from below the age of 30 years onward and show a rapid decline above 35 years. Also, understanding age-related decline in cochlear function reflected in DPOAEs at EHFs can help identify individuals with a greater risk of developing a hearing impairment. It can further guide early management, counseling, and follow-up assessments.

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