Extended High-Frequency Audiometry in Early Detection of Noise-Induced Hearing Loss in Occupational Settings

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Abstract

Objective: This study investigated the effect of noise exposure on extended high-frequency audiometry (EHFA) thresholds in an occupational setting. This study aimed to determine whether EHFA can provide insights into early cochlear changes that are undetectable through conventional methods and whether EHFA is more pronounced among workers exposed to higher noise levels. **Methods:** A retrospective, quantitative design was employed to analyze audiometric data from 180 employees across categories of three occupational noise exposure (<85, 85–104, and ≥105 dBA, A-weighted). Participants underwent conventional and EHFA, with thresholds measured from 500 to 20,000 Hz. Stratified random sampling was used to select individuals with normal thresholds at 500 to 4000 Hz (<25 dB HL). Multivariate analysis of variance and logistic regression were used to evaluate the effects of noise exposure, age, and years of service on EHFA thresholds. **Results:** The conventional audiometry thresholds were found between −10 and 50 dB HL, and the EHFA range was between −10 and 100 dB HL. The hearing threshold patterns were similar across the noise categories. No significant differences were observed in conventional audiometry and EHFA based on noise exposure categories ($P = 0.511$) or years of service ($P = 0.745$). However, significant associations with age were identified at 6000 Hz, 8000 Hz, and across all EHFA thresholds ($P < 0.05$). **Conclusion:** EHFA demonstrated limited sensitivity in differentiating noise-induced hearing loss across noise exposure categories, potentially reflecting the effectiveness of the hearing conservation program implemented. Age emerged as a significant factor influencing thresholds at high frequencies, highlighting the importance of considering age in EHFA.

Keywords: hearing loss, noise-induced, audiometry, occupational exposure

KEY MESSAGES:

(1) Age significantly influences extended high-frequency thresholds, highlighting the importance of considering age-related auditory decline when evaluating extended high-frequency audiometry in noise-exposed individuals.
(2) A well-implemented hearing conservation program may contribute to maintaining auditory thresholds in noise-exposed workers, potentially reducing the risk of noise-induced hearing loss.
(3) Extended high-frequency audiometry shows potential as a supplementary tool for assessing the effectiveness of hearing conservation programs in occupational settings, facilitating the identification of early auditory changes and assessment of the long-term effects of preventive measures.

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INTRODUCTION

Noise is typically defined as an undesirable sound that, when unmanaged, can lead to noise-induced hearing loss (NIHL).[1] The effects of noise exposure depend on its intensity, duration, and individual susceptibility; nonetheless, damage to inner ear hair cells, which often results in irreversible high-frequency hearing loss, tinnitus, or other

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auditory impairments, is most common.[2] Although the risks of noise have long been recognized, formal mitigation strategies only emerged later, with the first ear protection patent granted in 1864.[1] Continued neglect of these risks has contributed to NIHL becoming one of the most prevalent and preventable forms of hearing loss worldwide.[3]

In recent decades, the influence of noise exposure has become increasingly apparent at individual and societal levels. Rapid population growth and expanding industrialization have propelled the rise in the incidence of NIHL, particularly in work environments where occupational noise-induced hearing loss (ONIHL) is a global concern.[4] In the United States, approximately 30 million workers are exposed to noise levels exceeding the recommended 85 dBA.[5] Consequently, over 16% of adult hearing loss has been reported, equating to more than 4 million disability-adjusted life years.[6]

ONIHL extends beyond auditory function, imposing a significant burden on individual health and overall well-being. Individuals with hearing loss often experience frustration, anxiety, and depression due to the increased effort required in daily conversations and the stigma associated with hearing loss.[7] These psychosocial effects include social withdrawal, reduced self-confidence, and strained relationships, as ONIHL often goes unnoticed. As highlighted by the World Health Organization,[3] the subtle progressive nature of hearing loss often delays diagnosis and intervention, contributing to increased emotional and cognitive burden.

Within the workplace, ONIHL affects employee wellbeing and organizational efficiency. It can impair communication with colleagues, hinder response to auditory warning cues, and reduce the ability to follow instructions.[8] These effects may lower task accuracy, increase errors and accident risk, and reduce productivity, which is critical in high-risk environments such as mining and manufacturing.[9] Additionally, ONIHL can affect workplace dynamics. Abbasi *et al.*[8] found elevated workplace aggression and reduced work-related quality of life among individuals with NIHL, indicating broad effects on emotional regulation and job satisfaction.

To mitigate the effects of noise exposure, workplaces implement hearing conservation programs (HCPs), mandated in environments exceeding 85 dBA under the 1983 Hearing Conservation Amendment.[10] HCPs typically include noise monitoring, audiometric testing, and the provision of hearing protection devices (HPDs).[11] When properly fitted, HPDs can reduce exposure to 70 to 80 dBA,[12] offering a practical method of protection. Regular audiometric monitoring supports the early detection of hearing changes and the evaluation of the program's effectiveness.[13]

However, emerging evidence suggests that even with routine monitoring, NIHL may begin developing before changes are detected by conventional audiometry.[14] Conventional audiometry assesses frequencies up to 8000 Hz. In the early stages of NIHL, damage often begins in the outer hair cells of the cochlea beyond 8000 Hz,[15] allowing damage to progress undetected. Therefore, extended high-frequency audiometry (EHFA), which measures thresholds above 8000 Hz, may be better equipped at detecting early indicators of cochlear damage and facilitating early intervention.[14]

Several studies have shown that EHFA effectively detects early signs of hearing loss that may be undetected by conventional audiometry.[16-18] For instance, Xue *et al.*[19] found greater deterioration in EHFA thresholds than in conventional thresholds among individuals aged 18 to 42 years. In their study, the exposed group showed minimal differences in conventional thresholds but notable declines at extended high frequencies.[19] These findings highlight EHFA's sensitivity in detecting subtle auditory damage and its potential role in the early identification of NIHL.

Studies have shown that EHFA thresholds deteriorate significantly within the first decade of noise exposure, whereas similar changes appear later in conventional audiometry.[20] Early detection is especially important as industrial advances continue to elevate the risk of NIHL.[2,21] With increasing mechanization and persistent workplace noise, incorporating EHFA into routine screening may enable the early identification of at-risk individuals.[14] This may support timely interventions and help reduce the incidence and severity of permanent hearing loss among exposed workers.

Despite its potential, the use of EHFA in occupational settings remains limited, likely due to the lack of standardized testing procedures, calibration standards, and normative data for classifying hearing loss.[16,18] Additional barriers include the absence of threshold norms above 12,500 Hz, the need for specialized equipment, and time constraints.[22] Brown *et al.*[23] reported that 25% of practitioners cited inadequate equipment and 16% cited time demands or patient intolerance as reasons for not conducting EHFA. These challenges underscore the need to overcome practical and procedural barriers to fully realize EHFA's role in early NIHL detection.

In addition to equipment limitations, age-related variabilities in EHFA thresholds pose another barrier to its implementation. Studies have shown that early signs of auditory aging appear in the extended high-frequency (EHF) range as early as the pre-teen years, with deterioration becoming increasingly evident by the age of 30.[24,25] This variability also needs to be considered to distinguish between EHFA as an early indicator of NIHL and age-related deterioration in hearing thresholds.[25]

To investigate the influence of varying occupational noise exposure levels on EHFA, this study examined whether hearing loss in the EHF range is more pronounced among workers exposed to higher noise levels than their counterparts. EHFA was selected as the primary assessment tool because it demonstrated super sensitivity compared with conventional audiometry in detecting early cochlear damage. We hypothesized that if EHFA exhibits greater sensitivity, then participants with higher occupational noise exposure would show significantly elevated EHFA thresholds, despite having normal conventional hearing thresholds.

MATERIALS AND METHODS

Ethical clearance with number HUM004/0923 was obtained from the ethics committee at the Faculty of Humanities and Faculty of Health Sciences at the University of Pretoria.

This study adopted a retrospective cross-sectional design that utilized pre-existing audiometric data collected during routine hearing screenings performed at a large industry medical center. The screening took place between April and June 2023 and was aimed at evaluating the influence of different levels of occupational noise exposure on EHFA. A cross-sectional design was selected to enable comparisons of different exposure groups at a single time point, providing valuable insights into the effect of different levels of noise exposure on EHFA. The three different noise exposure categories selected enabled reliable comparisons among the groups. The equal number of participants from each exposure group ensured that the study had balanced representation across the three exposure categories. This facilitated clear comparisons of hearing thresholds in workers with different levels of noise exposure.

Permission was granted by the relevant management to undertake the study at a large industry medical center in South Africa. The medical center services different areas of occupational health risks within the company and performs routine medical surveillance screening on employees exposed to the levels of noise required for this study. The onsite clinicians who performed the hearing screenings were registered with the South African Society of Occupational Health Nursing Practitioners and the Health Professions Council of South Africa. Additionally, the medical center complies with the relevant International Organization for Standardization (ISO) regulations. The hearing screenings were conducted in a soundproof booth with low ambient background noise and acoustic interferences per ISO 8253-1.[26] Furthermore, the audiometer complied with the IEC 60645-1 regulations,[27] could test frequencies from 500 to 20,000 Hz and was calibrated annually in accordance with the ISO 389-1 and ISO 389-5 regulations.[28,29]

Participants

Before evaluating the hearing records for data collection, informed written consent was obtained from all participants. Participants were selected by stratified random sampling, which categorized them into subpopulations based on noise exposure levels.[30] We divided a study sample of 180 participants into three subgroups of 60. The sample size was deemed adequate, as the recommended minimum for conducting a multivariate analysis of variance (MANOVA) is 50 observations,[31] whereas regression analysis typically requires a minimum ratio of 10 observations per predictor.[32] With a total sample of 180 participants, our study exceeded both thresholds, allowing for up to 18 predictors in regression models. Given that our models included few predictors, the sample size was sufficient to ensure statistical power. Noise exposure categorization was based on the recommended exposure limits set by the National Institute for Occupational Safety and Health (NIOSH), which are set at 85 dBA over an 8-hour shift.[33] To determine an average rating, we converted measured noise levels (LReq, T) within the study workplace to 8-hour equivalent continuous rating levels (LReq,8h) using the formulas specified in the NIOSH.[33]

Sample Selection Criteria

Participants were selected from a workplace cohort via stratified random sampling based on their occupational noise exposure category. This method ensured balanced representation across three exposure categories, with 60 participants selected per group. All selected individuals met the inclusion and exclusion criteria, and no participants were excluded after selection. Sampling aimed to represent employees exposed to different occupational noise levels within the workplace. The final sample of 180 participants was drawn from a total pool of 867 eligible individuals who had undergone audiometric testing between April and June 2023. From this dataset, stratified random sampling was used to select 60 participants per noise exposure category, based on their exposure profiles. The following inclusion and exclusion criteria were applied:

Inclusion Criteria

(1) Participants who were 18–65 years of age.
(2) Exposed to different occupational noise levels over a period of 2 years or more.
(3) Presented with normal hearing levels on the conventional audiogram ($\leq$25 dB HL) at 500, 1000, 2000 and 4000 Hz to control for the presence of overt hearing loss.
(4) Participants who have had their hearing levels measured at 500–20,000 Hz in the period between April and June 2023.

Exclusion Criteria

(1) Participants with pre-existing hearing impairment (this does not include other comorbid conditions)
(2) Participants with incomplete audiometric data.

Grouping Method

Participants were grouped based on their levels of occupational noise exposure, as indicated in Table 1.

Table 1: Noise exposure categories ($N = 180$)

Noise Exposure Category	A-Weighted Sound Pressure Level	Hearing Screening Schedule	Hearing Protection Device Used
Category 1 ($n = 60$)	≤84 dBA ([LReq,8 h] ≤84 dBA)	Every 2 years	No
Category 2 ($n = 60$)	≥85 dBA but less than 104 dBA ([LReq,8 h] ≥85 dBA but ≤104 dBA)	Every year	Standard hearing protection (earplugs OR earmuffs)
Category 3 ($n = 60$)	≥105 dBA ([LReq,8 h) ≥105 dBA)	Every 6 months	Dual hearing protection (earplugs AND earmuffs used simultaneously)

Notes: dBA = decibel average-weighted, LReq,8h = 8-hour equivalent continuous rating levels

Hearing Screening Procedure and Equipment

The onsite audiometrists and audiologists conducted the hearing test. This entailed an otoscopic examination of the ears to determine the condition of the ear canal and identify any obstructions. Behavioral pure tone audiometry was completed for octave frequencies 500 to 8000 Hz and octave and interoctave frequencies 9000 to 20,000 Hz. Conventional audiometry and EHFA testing were performed in the same sitting in a sound-treated booth, which is calibrated annually and meets the maximum background noise level limits set out in ISO 8253.[28,29] The hearing tests were conducted as part of the employees' routine medical surveillance, with testing completed after at least 14 h had elapsed since noise exposure. HPDs that comply with ISO 4869-1[34] were deemed equivalent to meeting the requirement of 14 h free from noise exposure before audiometric testing.

A GSI Audiostar pro clinical audiometer with DD450 circumaural phones was used for conventional audiometry and EHFA. Calibration was performed annually by the manufacturing company in line with ISO 389 before data collection. Thresholds were obtained in decibel hearing level (dB HL) and 5 dB steps using the ascending–descending technique.[27] A threshold was the quietest sound measured in dB HL at each tested frequency, which participants were able to detect 50% of the time.[26] An absent or lack of response at the maximum intensity output of the EHF on the audiometer (viz. 80 dB HL for 14,000 Hz, 60 dB HL for 16,000 Hz, 30 dB HL for 18,000 Hz, and 15 dB HL for 20,000 Hz) was recorded as no response (NR).

All the thresholds were recorded on the GSI audiometric software, and conventional audiometry was further recorded on the audiometric software used by the employer for record-keeping of the participants' test results.

Data Collection

Data were collected using the employer's African Management Software (Enterprise) (AMSe), version 2022.07.02 (10,284). Participants were selected based on their departmental allocation, which corresponded with predefined occupational noise exposure levels. Departmental data and noise exposure classifications were readily accessible within the AMSe system. The researcher extracted a report from AMSe for routine hearing tests conducted between April and June 2023. The dataset was stratified into three noise exposure categories by specifying, within the software's search panel, the work environments and departments associated with each noise category.

Additional search filters were applied to include only tests classified as routine hearing assessments, audiograms recorded during the specified period, and participants with hearing thresholds ≤25 dB HL at the specified conventional frequencies. Only one audiogram per participant was selected for inclusion to avoid duplication. Although AMSe generated the conventional pure-tone threshold data, EHFA results were accessed separately through the GSI Suite. Using the participant data obtained from AMSe, the corresponding EHFA results were extracted and compiled to form complete audiometric profiles for each individual.

The compiled audiometric data were exported to Microsoft Excel, where each record was anonymized using alphanumeric participant codes. The final dataset included age, gender, years of service, and hearing thresholds at all tested frequencies for conventional (500–8000 Hz) and extended high-frequency (9000–20,000 Hz) ranges. For statistical analysis, NR thresholds at the maximum output level of the audiometer were recorded as inferred values, defined as 5 dB HL above the maximum output for each frequency: 85 dB HL at 14,000 Hz; 65 dB HL at 16,000 Hz; 35 dB HL at 18,000 Hz, and 20 dB HL at 20,000 Hz.

Statistical Analysis

Statistical analyses were conducted using IBM Statistic Package Social Sciences (SPSS Statistics, version 29). Figures and tables were created using Microsoft Excel for Microsoft 365, Version 2406 (Build 17726.20160), Microsoft Corporation, Redmond, WA, USA. Participants were categorized into three occupational noise exposure groups: category 1: ≤85 dBA, category 2: >85 to ≤104 dBA, and category 3: >104 dBA. These noise categories were analyzed in relation to participant age, gender, and years of service. Descriptive statistics [means, medians, standard deviations (SDs), and ranges] were calculated to summarize the demographic and audiometric characteristics within each noise category.

To assess the suitability of parametric analyses, we evaluated the normality of the dataset using skewness and kurtosis values. The data were found to be approximately normally distributed, justifying the use of parametric statistical techniques. There were only four missing values in the entire dataset: three participants failed to report their years of service, and one participant did not disclose their age. Given the minimal extent of missing data, multiple imputation was not considered necessary. These missing values were preserved in the dataset and addressed accordingly in the analyses. To identify outliers, we assessed standardized residuals, leverage values, and Cook's distance.

An observation was considered a potential outlier only if it exceeded established thresholds on all three diagnostics: a standardized residual greater than ±3.0, a leverage value above $2(k+1)/n$ (where k = number of predictors and n = sample size), and a Cook's distance greater than 1.0.[35] This conservative, combined approach ensures that only observations with unusual predictor values and a strong influence on the model were flagged, minimizing the risk of overidentifying outliers. Based on these criteria, no influential outliers were identified in the dataset.

MANOVA was conducted with noise exposure category as the primary independent variable, whereas age, sex, and years of service were included as covariates to adjust for potential confounding effects on hearing thresholds. This approach enabled the simultaneous evaluation of the effects of these variables across multiple frequencies and improved the power to detect whether noise exposure, age, and years of service have statistically significant effects on EHFA thresholds. In the model, age and years of service were treated as continuous variables, whereas noise exposure category was entered as a categorical variable, with three exposure levels. The degrees of freedom reported in MANOVA reflect the number of dependent variables, the model structure, and the inclusion of any significant effects. Subsequently, logistic regression analysis was used to explore the likelihood of elevated hearing thresholds in the EHFA range. In this model, hearing threshold outcomes were coded as binary (e.g., present vs. absent), with age, sex, and years of service entered as covariates. Logistic regression was appropriate for modeling binary outcomes and facilitated the estimation of odds ratios, thereby identifying significant risk factors for early hearing changes.

In addition, a regression model was used to evaluate the relationship between noise exposure levels and the means and SDs of hearing thresholds across frequencies. This provided further insight into the degree of hearing changes across the three noise exposure categories. To evaluate the practical significance of statistically significant findings, we calculated eta squared (η^2) values in conjunction with P values. Eta squared was used as a measure of effect size, indicating the proportion of variance in EHFA thresholds attributable to gender, age, and years of service.

Collinearity diagnostics were requested to evaluate the presence of multicollinearity among the independent variables during regression analyses. The variance inflation factor (VIF) values ranged from 1.019 to 2.081, and the corresponding tolerance values ranged from 0.481 to 0.981. These results fell well within acceptable limits (VIF <5.0, tolerance >0.2),[36] indicating that multicollinearity was not a concern.

RESULTS

A total of 180 participants with a mean age of 38.9 years (SD = 8.4) were assessed in the study, of which 21.8% were female. The mean ages across the exposure categories were similar, ranging from 37.7 years to 39.8 years. Occupational roles were recorded to provide contextual information

Table 2: Demographic characteristics of the total participant sample (*N* = 180 participants)

	Nonexposed (*n* = 60)	Exposed 85–≤103 dBA (*n* = 60)	Exposed ≥104 dBA (*n* = 60)
Sex [*n* (%)]			
Male	36 (60.0)	50 (83.3)	55 (91.7)
Female	24 (40.0)	10 (16.7)	5 (8.3)
Age (years) <break/>Mean (SD)	39.8 (7.8)	39.3 (9.9)	37.7 (7.5)
Range	22–60	22–62	27–59
Occupation [*n* (%)]			
Scientific and analytical personnel	15 (25)	0	0
Specialized technical personnel	0	9 (15.0)	18 (30.0)
Compliance, safety, and logistics personnel	25 (41.7)	0	
Technical and operational personnel	0	51 (85.0)	42 (70.0)
Administrative clerical personnel	6 (10.0)	0	0
General workers	14 (23.3)	0	0
Years of service (years) mean (SD)	9.6 (7.5)	12.9 (10.2)	10.9 (8.1)
Range	2–42	2–42	2–28

Notes: dBA = decibels A-weighted, SD = standard deviation

Table 3: Comparison of conventional hearing thresholds in decibel hearing level (dB HL) among the different exposure groups (*N* = 180 participants).

Exposure Category		500 Hz	1000 Hz	2000 Hz	3000 Hz	4000 Hz	6000 Hz	8000 Hz
≤84 dBA (*n* = 60)	Mean (SD)	3.3 (5.8)	5.4 (5.6)	5.8 (6.6)	6.7 (8.6)	8.0 (7.3)	8.0 (8.5)*	10.9 (9.8)*
	Median (range)	5.0 (−10–20)	5.0 (−10–20)	5.0 (−10–25)	5.0 (−10–25)	10.0 (−10–25)	5.0 (−10–35)	10.0 (−10–40)
85–104 dBA (*n* = 60)	Mean (SD)	4.1 (5.1)	5.6 (5.9)	4.8 (6.7)	6.0 (8.5)	9.7 (8.6)	6.6 (8.9)*	10.5 (11.5)*
	Median (range)	5.0 (−10–20)	5.0 (−10–20)	5.0 (−10–25)	5.0 (−10– 25)	10.0 (−10– 25)	5.0 (−10– 40)	10.0 (−10– 45)
≥105 dBA (*n* = 60)	Mean (SD)	1.7 (6.3)	4.9 (6.7)	4.3 (8.0)	6.3 (6.9)	8.5 (7.5)	6.3 (8.2)*	7.6 (10.4)*
	Median (range)	0.0 (−10–20)	5.0 (−10–20)	5.0 (−10–25)	5.0 (−10–25)	7.5 (−10–25)	5.0 (−10–25)	5.0 (−10–50)

Notes: dBA = decibels A-weighted, Hz = hertz, SD = standard deviation; * Statistically significant effects of age on hearing thresholds ($P < 0.001$, MANOVA), with no significant differences found across noise exposure groups or years of service.

regarding participants' socioeconomic backgrounds. Although direct educational data were not available, occupational categories (e.g., specialized technical personnel vs. general workers) offer proxy indicators of potential socioeconomic differences among groups. Occupations varied by exposure level, with nonexposed participants mainly occupying scientific, administrative, and compliance roles, whereas the exposed groups were predominantly specialized technical and operational personnel. General workers, comprising cleaning and security personnel were only present in the nonexposed group. Years of service showed a wide range across groups, with higher mean service time noted among those exposed to moderate noise levels. Descriptive statistics are provided for participant characteristics; however, no formal group comparisons were conducted for demographic variables, as these were used as covariates in the subsequent MANOVA models. Detailed information is shown in Table 2.

Table 3 presents the pure-tone air-conduction thresholds (in dB HL) across the conventional audiometric frequencies (500–8000 Hz), which ranged from −10 to 50 dB HL. Median thresholds were largely consistent, not exceeding 10 dB HL. At 6000 and 8000 Hz, mean thresholds were slightly higher in the ≤84 dBA group, compared with the other groups.

Across all exposure categories, similar patterns of hearing thresholds were observed, with a gradual increase in thresholds noted between 2000 and 8000 Hz [Figure 1].

A four-frequency pure-tone average calculated using thresholds at 500, 1000, 2000, and 4000 Hz yielded a mean of 5.8 dB HL (SD 4.9) across the three noise exposure groups. By contrast, mild elevations were noted in the elevated frequencies, with the high-frequency pure-tone average (HFPTA) based on thresholds at 4000, 6000, and 8000 Hz, showing a mean of 8.7 dB HL (SD 7.5). Figure 2 displays the threshold distributions at each frequency in conventional audiometry (500–8000 Hz). Individual variation within each noise exposure category was found, with notable stretched plots observed across all groups, reflecting wide interquartile ranges. Longer whiskers indicated greater variability in hearing thresholds among participants. In addition, several outliers were noted even though all thresholds remained within the clinically normal hearing range (≤25 dB HL).

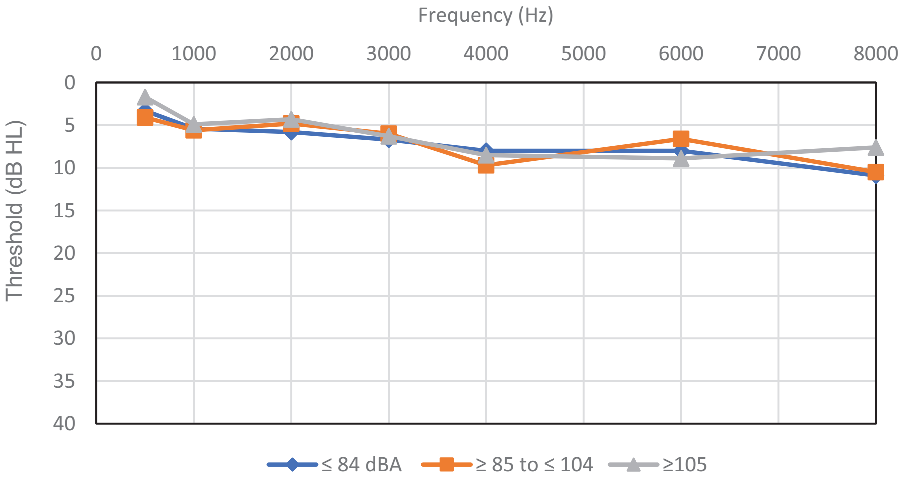

Figure 1: Patterns of distribution of mean thresholds obtained on conventional audiometry between the noise categories.

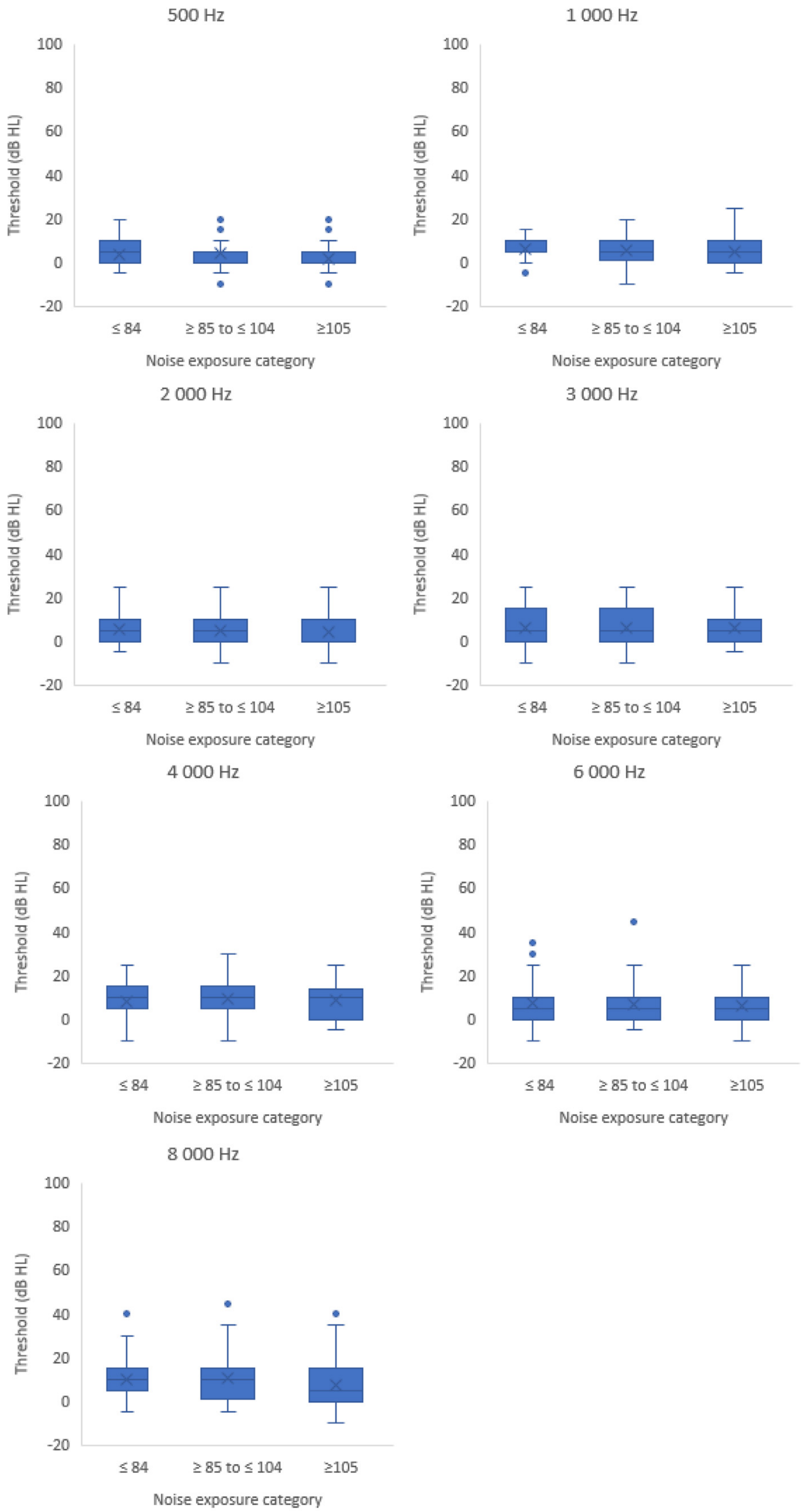

Figure 2: Box plots showing pure-tone air conduction thresholds in decibel hearing level (dB HL) by noise exposure category for conventional audiometric frequencies.

The EHF thresholds (9000–20,000 Hz) are presented in Table 4, stratified by occupational noise exposure category.

Unlike conventional audiometry, significant variability was found within the median EHF threshold ranges, with differences exceeding 10 dB HL as frequency increased. Across frequencies, elevated thresholds were observed even in the lowest exposure category (≤84 dBA), with group means exceeding 10 dB HL from 9000 Hz. Between 11,500 and 16,000 Hz, a noticeable rise in the mean thresholds was observed across all exposure categories, with 16,000 Hz being most affected [Figure 3].

The box plots in Figure 4 present the distribution of EHF thresholds at each frequency across the three categories of noise exposure levels. A stretched appearance was evident at several frequencies, with wide interquartile ranges and long whiskers observed at high frequencies. This result may be due to the increased variability in hearing thresholds among individuals within the same exposure category. The variability was pronounced at 16,000 Hz, with a higher number of outliers compared with conventional audiometry, reflecting greater individual differences in EHFA. These results highlight the dispersion in threshold sensitivity at the upper limits of the auditory range, whereas the threshold clustering at the maximum output level suggested a ceiling effect. Detailed information showing the threshold distributions for each EHF in the noise categories can be found in Figure 4. on conventional audiometry and extended high-frequency for the noise exposure categories.

Figure 5 presents the distribution of maximum thresholds across various noise exposure categories. No significant differences were observed between the groups for the conventional and EHF thresholds. A notable increase in thresholds was observed between 10,000 and 14,000 Hz, followed by an apparent decline from 16,000 Hz onward. This downward trend likely reflects audiometric output limitations and the increasing number of non-responses at audiometer output levels, rather than an actual improvement in hearing sensitivity.

Thresholds at 18,000 and 20,000 Hz were mostly underestimated due to output limits of the audiometer (maximum output: 30 dB HL at 18,000 Hz and 15 dB HL at 20,000 Hz). This limitation is further illustrated by the proportion of absent thresholds, with 46% of thresholds absent at 20,000 Hz [Figure 6].

The extended HFPTA at the EHFs (9000–20,000 Hz) calculated across the categories was 57.3 dB HL (mean = 21.0; SD = 15.5). Age-related associations with EHF thresholds were further highlighted by significant effects observed across all EHF thresholds ($P < .001$), with partial ^{2} ranging from 0.053 (small) to 0.263 (large). The largest effect was at 16,000 Hz (F = 61.6, $P < 0.001$, partial $\eta^2 = 0.263$). Detailed information on the effect sizes can be found in Table 5.

Table 4: Comparison of extended high-frequency hearing thresholds in decibel hearing level (dB HL) among the different exposure groups ($N = 180$ participants).

Exposure Category		9000 Hz	10,000 Hz	11,500 Hz	12,500 Hz	14,000 Hz	16,000 Hz	18,000 Hz	20,000 Hz
≤84 dBA (n = 60)	Mean (SD)	11.3 (11.0)*	12.2 (12.7)*	16.9 (16.6)*	22.3 (21.2)*	30.2 (23.8)*	36.4 (21.9)*	26.9 (11.1)*	16.1 (6.7)*
	Median (range)	10.0(−5–50)	10.0 (−10–55)	15.0 (−5–75)	15.0 (−10–85)	25.0 (−10–85)	40.0 (−10–65)	30.0 (−10–35)	20.0 (−10–20)
85–104 dBA (n = 60)	Mean (SD)	11.6 (13.8)*	11.1 (18.5)*	16.0 (21.6)*	21.9 (25.5)*	28.2 (27.6)*	32.7 (24.8)*	24.2 (14.3)*	14.1 (8.0)*
	Median (range)	10.0 (−10–60)	5.0 (−10–95)	10.0 (−10–100)	15.0 (−10–95)	25.0 (−10–85)	35.0 (−10–65)	30.0 (−10–35)	20.0 (−10–20)
≥105 dBA (n = 60)	Mean (SD)	10.7 (12.2)*	11.0 (14.5)*	14.3 (15.5)*	19.0 (18.0)*	29.8 (23.1)*	33.8 (22.6)*	25.5 (13.0)*	16.2 (6.1)*
	Median (range)	7.5 (−10–60)	7.5 (−10–95)	10.0 (−10–100)	15.0 (−10–95)	25.0 (−10–85)	30.0 (−10–65)	30.0 (−10–35)	20.0 (−10–20)

Notes: Absent thresholds were substituted with thresholds 5 dB above the maximum intensity; dBA = decibels A-weighted, Hz = hertz, SD = standard deviation; *Correspondence to Statistically significant effects of age on hearing thresholds ($P < 0.001$, MANOVA), with no significant differences found across noise exposure groups or years of service.

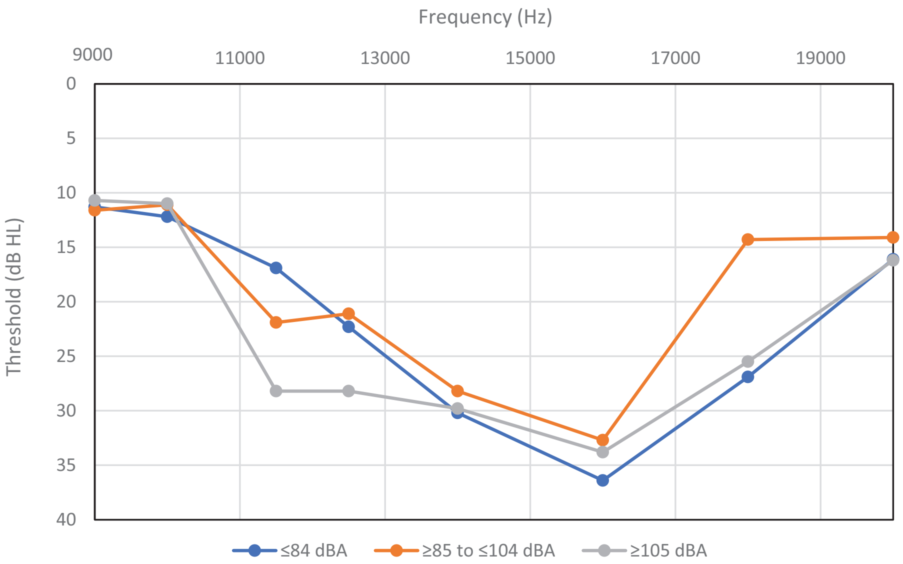

Figure 3: Patterns of distribution of mean thresholds attained on extended high-frequency among the noise categories.

One-way MANOVA was performed to examine the effects of age, exposure category, and years of service on the EHFA thresholds. The degrees of freedom reported reflect the inclusion of multiple EHFA thresholds as dependent variables, noise exposure category as a categorical independent variable, and age and years of service as continuous covariates. Significant effects were found for age and EHFA (Wilk's $\Lambda = 0.669$, $F(15, 157) = 5.18$, $P < 0.001$, partial $\eta^2 = 0.33$), with age accounting for approximately 33% of the variance in the outcomes. The highest effect was observed at 16,000 Hz ($F = 61.6$, $P < 0.001$, partial $\eta^2 = 0.263$), further confirming the association of age on hearing thresholds at high frequencies, notably around 16,000 Hz. No significance was shown for years of service (Wilk's $\Lambda = 0.934$, $F(15, 157) = 0.74$, $P = 0.745$, partial $\eta^2 = 0.07$) across all conventional audiometry thresholds and EHF thresholds. The noise exposure categories showed no significant differences across all tested conventional and EHF thresholds, as indicated by multivariate analysis (Wilk's $\Lambda = 0.837$, $F(30, 314) = 0.97$, $P = 0.511$, partial $\eta^2 = 0.09$) and follow-up tests ($P > 0.05$). Moreover, small to negligible effect sizes (partial $\eta^2 = 0.001$–0.028) were noted between 6000 and 20,000 Hz in contrast to age-related effects. Detailed information can be found in Table 6.

A logistic regression model analyzed the probability of threshold detection at the EHF thresholds (NR = 0; response = 1), including age, years of service, and exposure category as predictors. The binary outcome (0 = NR, 1 = present) was modeled for each frequency. The logistic regression models demonstrated acceptable fit, explaining between 24.9% and 29.9% of the variability in threshold detection outcomes across 16,000, 18,000, and 20,000 Hz (pseudo $R^2 = 0.249$–0.299). Model diagnostics were within acceptable ranges (e.g., log-likelihood = 136.142–207.264; Alkaline information criterion (AIC) = 0.150–0.224). Although the main effects of age, years of service, sex, and noise exposure category were included in the logistic regression models, interaction terms were not assessed because of sample size limitations. Among the variables evaluated, age consistently emerged as the only statistically significant predictor of EHFA threshold detection at 16,000 and above. These results highlight the importance of considering age-related auditory changes when interpreting EHFA results, as the likelihood of detecting thresholds decreases significantly with increasing age [Table 7].

DISCUSSION

Conventional audiometry remains the gold standard for detecting ONIHL; however, EHFA has emerged as a promising supplementary tool, particularly for the early detection of ONIHL.[17,18] Although noise exposure is considered a critical risk factor for hearing loss, in this study, age showed a strong association with EHF thresholds across all the noise exposure categories, despite the duration of exposure. This finding is aligned with prior research demonstrating that hearing sensitivity declines significantly with age, particularly in the EHF range.[24,38,39]

The significant deterioration in EHF thresholds associated with age found in this study was consistent with findings by Mishra *et al.*,[24] who reported EHF hearing loss from as early as 30 years of age in young adults with normal conventional audiograms. Similarly, Gajendran *et al.*[40] observed significant changes in EHFA ranges of young medical students using personal listening devices. These studies emphasize the cumulative effects of age on EHFA

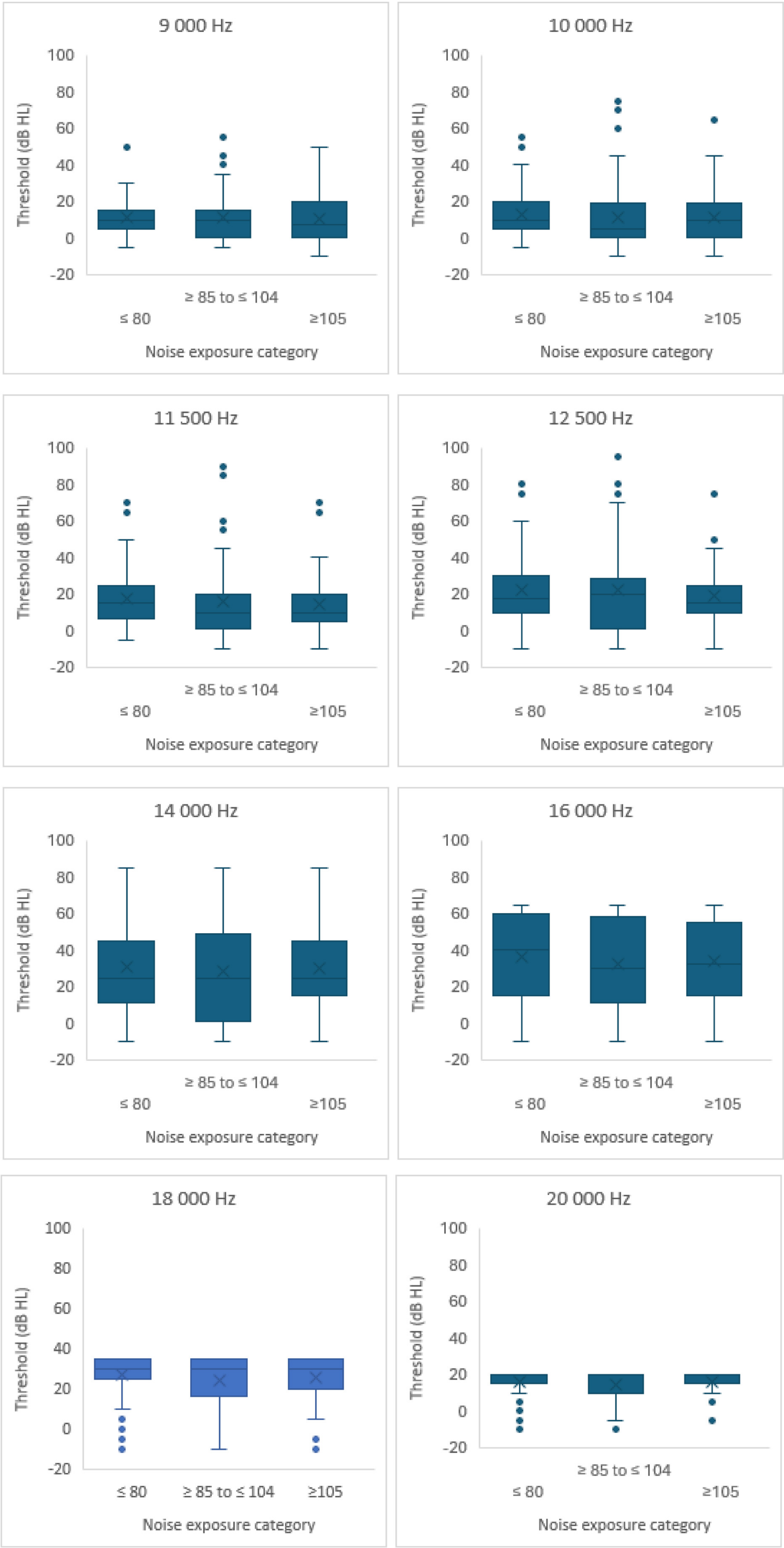

Figure 4: Box plots showing pure-tone air conduction thresholds in decibel hearing level (dB HL) by noise exposure category for extended high-frequencies . No response values were substituted with 5 dB HL above the audiometer output.

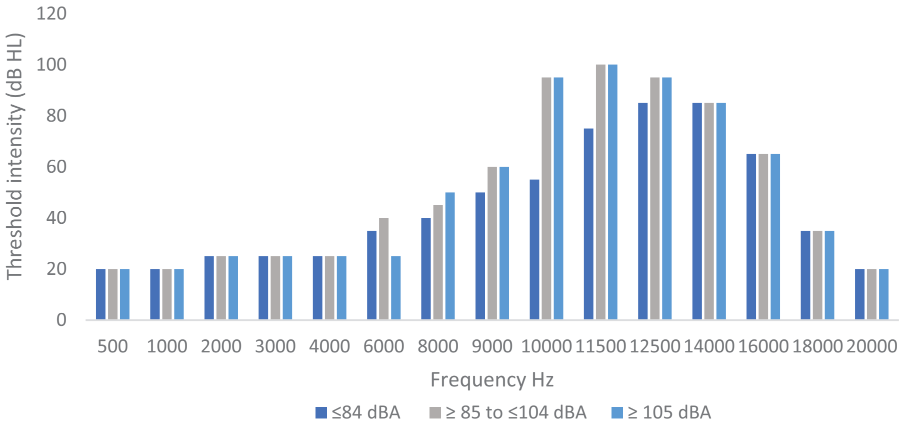

Figure 5: Patterns of distribution of maximum thresholds attained on conventional audiometry and extended high-frequency for the noise exposure categories.

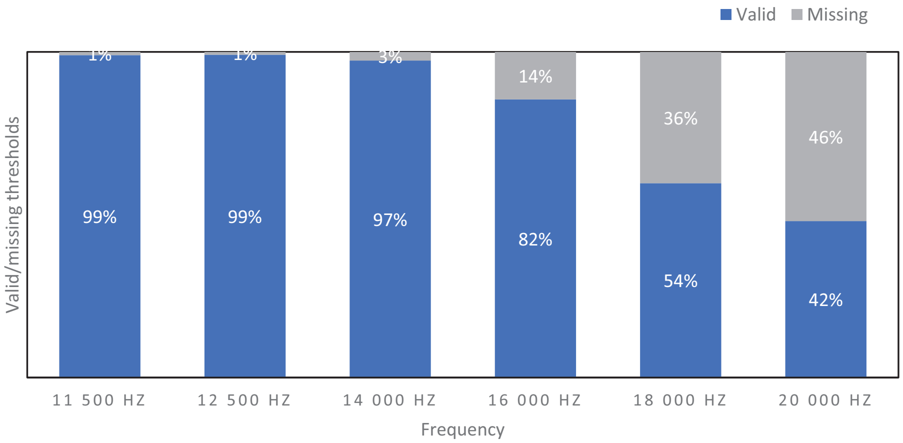

Figure 6: Frequencies with absent thresholds at maximum intensities ($N = 180$). Max intensities across 11,500–20,000 Hz; 95 dB HL for 11,500 Hz, 90 dB HL for 12,500 Hz, 80 dB HL for 14,000 Hz, 60 dB HL for 16,000 Hz, 30 dB HL for 18,000 Hz, and 15 dB HL for 20,000 Hz.

thresholds. In the context of the current study, the findings underscore the role of age on hearing sensitivity at EHFs, even in the presence of occupational HCPs.

The large effect sizes for age at 14,000 to 18,000 Hz ($\eta^2 = 0.199$–0.263) found in this study mirrored those of Luengrungrus *et al.*,[41] who found threshold ceilings at these frequencies in individuals over 60. These findings further reinforce the idea that age, rather than noise exposure alone, plays a significant role in the deterioration of hearing sensitivity at elevated frequencies. Moreover, the consistency of these results across different studies suggested that age-related contributions must be included when evaluating EHFA, particularly in populations exposed to noise.

Unexpectedly, no statistically significant differences were observed in EHF thresholds across different noise exposure groups or years of service, after adjusting for age. This result contradicted previous studies that suggested that EHFA is highly sensitive in detecting early NIHL and that elevated thresholds are correlated with noise intensity and exposure

Table 5: Frequencies with significant effects of age on hearing thresholds (multivariate analysis of variance—age, years of service, and noise exposure category)

Frequency	6000 Hz	8000 Hz	9000 Hz	10,000 Hz	11,500 Hz	12,500 Hz	14,000 Hz	16,000 Hz	18,000 Hz	20,000 Hz
F-statistics	20.4	12.6	9.6	20.6	24.6	32.6	42.5	61.6	44.0	30.0
Significance	$P < 0.001$	$P < 0.001$	$P < 0.002$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$
Effect size* (partial η^2)	Medium (0.107)	Medium (0.069)	Small (0.053)	Medium (0.108)	Medium (0.126)	Large (0.160)	Large (0.199)	Large (0.263)	Large (0.205)	Large (0.147)

Notes: Hz = hertz; *Effect sizes following the guidelines of Maggino[37]: small $< \eta^2 \approx 0.06$; medium to large $\eta^2 \approx 0.06$ to 0.14; large $> \eta^2 \approx 0.14$.

Table 6: Between-group differences in thresholds by noise exposure category (multivariate analysis of variance—age, years of service, and noise exposure category)

Frequency	6000 Hz	8000 Hz	9000 Hz	10,000 Hz	11,500 Hz	12,500 Hz	14,000 Hz	16,000 Hz	18,000 Hz	20,000 Hz
F-statistics	0.047	0.833	0.001	0.405	0.214	0.056	0.644	0.592	0.711	2.448
Significance	P = 0.954	P = 0.436	P = 0.999	P = 0.667	P = 0.807	P = 0.946	P = 0.526	P = 0.554	P = 0.493	P = 0.089
Effect size* (partial η^2)	Small (0.001)	Small (0.010)	None (0.000)	None (0.005)	None (0.004)	None (0.001)	Small (0.007)	None (0.007)	None (0.008)	None (0.028)

Notes: Hz = hertz;* Effect sizes following the guidelines of Maggino[37]: small $< \eta^2 \approx 0.06$; medium to large $\eta^2 \approx 0.06$ to 0.14; large $> \eta^2 \approx 0.14$

duration.[16,18] For instance, Ma *et al.*[42] reported higher EHF thresholds in noise-exposed pilots compared with unexposed individuals, whereas Tinazli and Tinazli[43] found strong associations between EHFA and early NIHL in hunters. The differences in findings between this study and others reporting significant associations between noise exposure and EHF thresholds may be due to several methodological and interacting mechanisms.

Firstly, the inclusion of only individuals with normal conventional thresholds in this study may have introduced a selection bias favoring cochlear integrity, obscuring the effects of noise exposure. For example, in contrast to the current study, the inclusion criteria for participants in the studies by Ma *et al.*,[42] as well as Tinazli and Tinazli,[43] did not require normal thresholds on conventional audiometry. Secondly, differences in the nature and pattern of noise exposure, such as low impulsiveness or kurtosis in industrial noise versus gunshot or aviation noise, may have influenced the discrepancies in findings. Different occupations exhibit distinct levels of noise exposure in terms of frequency and duration, and complex noise exposure has been demonstrated to elevate the risk of severe ONIHL among workers.[44]

Another potential explanation for the lack of significant findings in the current study is the effectiveness of established safety measures. Couto Lopes *et al.*[45] reported an inverse relationship between hearing loss prevalence and HCPs, indicating a significant decline in the incidence of ONIHL in organizations where robust HCPs are implemented. Moreover, Lopes *et al.*[46] found that workplace safety measures, such as established HCPs where administrative controls are applied and HPDs are provided, have been shown to reduce ONIHL prevalence by 23%. As a result of these safety measures, the cumulative noise exposure for participants in the current study may not have reached levels sufficient to produce measurable changes in EHF thresholds. This protective effect may not only have delayed or reduced the onset of detectable hearing loss but also suggested that EHFA may assist in monitoring the effectiveness of HCPs over time.

This study has several limitations that should be acknowledged. This study was conducted in a single

Table 7: logistic regression results predicting detection of extended high-frequency audiometry thresholds at 16,000, 18,000, and 20,000 Hz.

Predictor and Statistic	16,000 Hz	18,000 Hz	20,000 Hz
85–104 dBA *B* (SE)	−0.644 (0.619)	−0.117 (0.444)	0.315 (0.429)
OR (95% CI)	0.525 (0.156, 1.767)	0.889 (0.373, 2.122)	1.370 (0.591, 3.174)
P-value	0.298	0.792	0.463
≥105 dBA *B* (SE)	−0.947 (0.635)	−0.164 (0.442)	−0.332 (0.438)
OR (95% CI)	0.388 (0.112, 1.348)	0.848 (0.357, 2.016)	0.718 (0.304, 1.694)
P-value	0.136	0.710	0.449
Gender *B* (SE)	−0.620 (0.612)	0.304 (0.452)	−0.511 (0.438)
OR (95% CI)	0.538 (0.162, 1.784)	1.355 (0.558, 3.288)	0.600 (0.254, 1.417)
P-value	0.311	0.502	0.244
Age *B* (SE)	−0.131 (0.040)	−0.150 (0.034)	−0.139 (0.035)
OR (95% CI)	0.812 (0.702, 0.939)	0.853 (0.0798, 0.912)	0.870 (0.813, 0.932)
P-value	0.001	0.001	0.001
Years of service *B* (SE)	−0.004 (0.033)	0.028 (0.031)	0.025 (0.033)
OR (95% CI)	0.996 (0.934, 1.062)	1.028 (0.967, 1.093)	1.025 (0.961, 1.093)
P-value	0.901	0.372	0.457

Notes: $P < 0.05$ is considered significant; B = regression coefficient, CI = confidence interval, dBA = decibels A-weighted, Hz = hertz, OR = odds ratio, SE = standard error metallurgical occupational setting with an established HCP, which may limit the generalizability of the findings to other industries or workplaces without such programs. Noise exposure was categorized by work position rather than measured individually, which could mask variability in individual noise doses and affect exposure classification accuracy. The retrospective cross-sectional design prevented longitudinal tracking of hearing changes, limiting insight into the progression of EHF threshold shifts over time. Participants included only those with normal conventional audiometric thresholds, potentially excluding individuals with early or established NIHL and limiting the assessment of EHFA sensitivity across different hearing profiles. Audiometric equipment constraints limited threshold detection at frequencies of 16,000 Hz and above, with maximum output levels capped at 60 dB HL at 16,000 Hz and even lower at 18,000 and 20,000 Hz. This resulted in ceiling effects and may have underestimated actual thresholds, as nearly half of the participants had NRs at 20,000 Hz. Although sex was included as an independent variable in the analyses and was not found to be a statistically significant predictor of EHF thresholds, this imbalance should be considered when interpreting and generalizing the results. Multivariate analyses adjusted for age, sex, years of service, and noise exposure category, but interaction effects among these variables (e.g., age × years of service or age × noise exposure) were not explored. This was due to statistical power limitations associated with the sample size. Future research with large, diverse cohorts should explore how these variables may interactively influence EHF thresholds.

Future research should prioritize prospective longitudinal studies to clarify the progression of EHF hearing changes in relation to individual noise exposure measurements. Including participants with a wide range of hearing abilities, including mild or moderate NIHL, will be important to validate the utility of EHFA for early detection across diverse auditory profiles. Given that the output limitations of audiometers may underestimate EHF thresholds at frequencies above 16,000 Hz and the technical challenges in increasing transducer output at high frequencies, future studies could explore alternative assessment tools, such as otoacoustic emissions or speech-in-noise tests. These methods may offer additional insights into cochlear function and real-world hearing ability where EHFA measurement is limited by equipment constraints. The development and validation of age- and sex-specific normative data for EHFA are essential to improve diagnostic accuracy. Additionally, studies evaluating the feasibility, cost-effectiveness, and integration of EHFA into existing occupational HCPs, especially in resource-limited settings, are needed to support practical implementation.

CONCLUSION

This study investigated the effect of age, years of service, and occupational noise exposure on EHFA. Contrary to our hypothesis, noise exposure and years of service were not significant predictors of EHF thresholds after accounting for age. Age emerged as a significant determinant of EHFA, corroborating previous evidence that age-related changes significantly affect EHF thresholds. Although EHFA was not proven to be an effective early indicator of ONIHL in this study, it demonstrated potential value in specific occupational settings and as a tool for monitoring the effectiveness of HCPs.

Availability of Data and Materials

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions

De Wet Swanepoel led the conceptualization of the research and developed the methodology with substantial support from Leigh Biagio de Jager. Hilda Mkwanazi contributed to data curation and the initial drafting of the manuscript, while Marien Graham conducted the formal data analysis. All authors actively participated in writing, reviewing, and editing the manuscript.

Ethics Approval and Consent to Participate

Ethics approval with number HUM004/0923 was obtained from the University of Pretoria's Faculty of Humanities and Faculty of Health Sciences Department. Informed consent was obtained from all individual participants included in the study.

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Conflict of Interests

The authors declare no conflicts of interest.

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