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Global Burden and Future Projections of Occupational Noise Exposure-related Hearing Loss: An Age-Period-Cohort and ARIMA Modeling Study Based on GBD Data (1990-2021)

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ABSTRACT

Objectives: To quantify the global burden of occupational noise-induced hearing loss (ONHL) from 1990 to 2021 by sex, age, and Socio-demographic Index (SDI), and to project its future trends through 2035. **Methods:** Data on disability-adjusted life years (DALYs), age-standardized DALY rates (ASDRs), and summary exposure values (SEVs) of ONHL were extracted from the GBD 2021 study. Joinpoint regression was used to estimate annual percent changes in ASDRs. An age-period-cohort model assessed the effects of age, period, and cohort. Autoregressive integrated moving average (ARIMA) models forecasted DALY trends from 2025 to 2035. **Results:** Globally, ONHL-related DALYs increased from 3.84 million in 1990 to 7.85 million in 2021, with the highest relative increases in low- and middle-SDI regions. Males consistently had higher burden than females. DALYs peaked in midlife (ages 50-59), while age-specific DALY rates peaked at older ages (60-74). APC analysis revealed significant age effects across all SDI levels, while period and cohort effects were limited. ARIMA models predicted that global ONHL DALYs would reach 9.65 million by 2035, a 22.97% increase from 2021, with largest increases expected in those aged 55-59. **Conclusions:** Occupational noise–induced hearing loss remains a growing global public health challenge, particularly among male workers in lower-SDI regions. Continued increases are projected over the next decade. These results underscore the urgent need for strengthened hearing conservation strategies and targeted prevention policies to reduce ONHL burden worldwide.

1. Introduction

Occupational noise exposure remains one of the most common and preventable occupational hazards worldwide, affecting workers across diverse industries and socioeconomic settings [1]. Prolonged exposure to hazardous sound levels, typically defined as ⩾85 dBA over an 8-hour time-weighted average, can cause irreversible noise-induced hearing loss (NIHL), tinnitus, and communication difficulties, and is also associated with extra-auditory health effects such as cardiovascular disease, depression, balance disorders, and reduced quality of life [2]. Globally, the prevalence of occupational noise exposure varies but remains substantial: approximately 15-20% of workers in high-income countries report exposure, with even higher proportions observed in industrializing nations due to rapid shifts toward manufacturing and construction [3][4].

According to the Global Burden of Disease (GBD) 2019 study, NIHL affects millions of working-age adults, contributing significantly to the global burden of disability [5]. Occupational noise is estimated to account for ~16% of disabling hearing loss worldwide, with marked disparities by region, sex, and socioeconomic status [3]. While the highest prevalence

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occurs in traditionally high-risk sectors such as mining, construction, and manufacturing workers across diverse industries may be exposed to hazardous noise. Beyond auditory consequences, chronic noise exposure can trigger sustained activation of the autonomic nervous and endocrine systems, increasing the risk of hypertension, ischemic heart disease, and adverse pregnancy outcomes [6][7].

Despite decades of regulatory standards and hearing conservation programs, reductions in occupational noise exposure have been uneven. Surveillance data from high-income countries suggest a modest decline in some sectors, but global analyses indicate increasing exposure in low- and middle-income countries [8][9]. Compounding this challenge, "hidden hearing loss" due to cochlear synaptopathy may occur without detectable changes in audiometric thresholds, suggesting that current monitoring practices may potentially leading to an underestimation of the true disease burden [10].

The GBD framework offers a unique opportunity to quantify the spatiotemporal patterns of disease burden attributable to occupational noise across 204 countries and territories, using standardized metrics such as age-standardized incidence rates (ASIR), disability-adjusted life years (DALYs), and estimated annual percentage change (EAPC) [11]. However, detailed global analyses focusing exclusively on occupational noise-integrating geographic, demographic, and temporal dimensions-remain scarce.

Therefore, this study aims to describe the global, regional, and national burden of disease attributable to occupational noise from 1990 to 2021, analyze temporal trends using ASRs and EAPC, and assess disparities by sex, age group, and Socio-demographic Index (SDI). Findings from this work will provide an updated evidence base for occupational health policies, guide resource allocation, and inform preventive strategies to mitigate the burden of occupational noise exposure worldwide.

2. Materials and Methods

2.1. Data Sources

Data on disability-adjusted life years (DALYs), age-standardized DALY rates (ASDRs), and summary exposure values (SEVs) attributable to ONHL were obtained from the Global Burden of Disease (GBD) 2021 study, which covers 204 countries and territories. Results were extracted using the GBD online query tool (https://vizhub.healthdata.org/gbd-compare/), disaggregated by year (1990-2021), sex, age, and Socio-demographic Index (SDI) quintiles (high, high-middle, middle, low-middle, and low).

2.2. Disease Burden Metrics

DALYs were defined as the sum of years of life lost (YLLs) and years lived with disability (YLDs). Age-standardized DALY rates were calculated using the GBD world standard population. SEV reflects the weighted exposure distribution of a risk factor within a population, scaled from 0% (no exposure) to 100% (maximum risk exposure). The average annual percentage change (AAPC) in ASDRs was used to quantify temporal trends.

2.3. Joinpoint Regression Analysis

Joinpoint regression was used to explore temporal trends in ASDRs from 1990 to 2021 at the global and SDI regional levels. We applied the Joinpoint Regression Program (Version 4.9.1.0, National Cancer Institute, USA) to identify points where significant changes in trend occurred, estimating the annual percentage change (APC) and AAPC with 95% confidence intervals (CIs). Statistical significance was defined as two-sided *P* < 0.05.

2.4. Age-Period-Cohort (APC) Model

To disentangle the effects of age, period, and birth cohort on DALY and SEV trends, we applied intrinsic estimator-based APC models using R software (Version 4.1.2) and the "apc" package. Data were grouped into consecutive 5-year age bands based on GBD classification. Net drift, local drift, period rate ratios, and cohort rate ratios were calculated. Statistical significance was assessed using Wald chi-square tests, with *P* < 0.05 considered significant.

2.5. ARIMA Forecasting

Autoregressive integrated moving average (ARIMA) models were constructed to project global DALY counts and rates from 2025 to 2035. Time series stationarity was assessed using the augmented Dickey-Fuller test. Optimal model parameters (p, d, q) were selected based on the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). Forecasts were generated using the "forecast" package in R.

2.6. Statistical Software

Analyses were performed using R software (Version 4.1.2), including the "apc" and "forecast" packages, and the Joinpoint Regression Program (Version 4.9.1.0). Figures were plotted using R and GraphPad Prism 9.0.

2.7. Ethical Considerations

This study used publicly available, de-identified data from the GBD 2021 database. Ethical approval and informed consent were therefore not required.

3. Results

3.1. Changes in DALYs due to ONHL across global, high SDI, high-middle SDI, middle SDI, low-middle SDI, and low SDI Regions (1990-2021).

As shown in Table 1, from 1990 to 2021, the global number of DALYs increased from 3.838 million to 7.847 million, representing a rise of 104.46%. During the same period, DALYs in high-SDI, high-middle SDI, middle SDI, low-middle SDI, and low-SDI regions increased by 64.93%, 94.30%, 111.51%, 114.64%, and 129.08%, respectively. Globally, the ASDR showed a significant upward trend over time, rising from 84.28 per 100,000 population in 1990 to 91.12 per 100,000 in 2021, with a statistically significant trend (AAPC = 0.25%, P < 0.01). Both high-SDI

and high-middle SDI regions demonstrated significant increases in ASDR over time (AAPC = 0.16% and 0.46%, respectively; P < 0.01, Table 1). In contrast, no significant ASDR trends were observed in middle-SDI or low-middle SDI regions (AAPC = -0.01%, both P > 0.05, Table 1). Notably, the ASDR in low-SDI regions exhibited a significant decreasing trend over time (AAPC = -0.08%, P < 0.01, Table 1).

Table 1 - Changes in disease burden of ONHL across global, high SDI, high-middle SDI, middle SDI, low-middle SDI, and low SDI Regions (1990-2021).

Region	All-Age DALYs (95% UI) (×10^4)		Age-Standardized Rate (95% UI) (/100,000)		1990-2021	
	1990	2021	1990	2021	AAPC (95% CI) (%)	t-value
Global	383.81 (263.09, 537.33)	784.74 (531.36, 1098.08)	84.28 (57.62, 118.17)	91.12 (61.98, 127.20)	0.25 (0.24,0.26) *	61.54
High SDI	44.54 (30.25, 62.94)	73.46 (49.51, 103.96)	43.46 (29.37, 61.72)	45.56 (30.66, 64.63)	0.16 (0.13,0.19) *	10.40
High-Middle SDI	85.14 (57.71, 119.64)	165.43 (111.22, 234.30)	79.32 (53.63, 111.58)	91.40 (61.49, 127.84)	0.46 (0.45,0.47) *	78.44
Middle SDI	142.50 (97.29, 199.86)	301.40 (202.71, 424.19)	107.50 (72.62, 151.54)	107.22 (72.41, 150.41)	-0.01 (-0.02,0.00)	-1.82
Low-Middle SDI	76.78 (53.20, 107.45)	164.80 (113.77, 228.68)	97.38 (66.41, 135.99)	96.87 (66.53, 135.34)	-0.01 (-0.04,0.01)	-1.25
Low SDI	34.56 (23.69, 48.07)	79.17 (54.40, 110.27)	114.32 (78.70, 157.77)	111.72 (77.54, 154.69)	-0.08 (-0.10, -0.05) *	-6.69

*P＜0.01

Table 2 - APC model of DALYs for ONHL across global, high SDI, high-middle SDI, middle SDI, low-middle SDI, and low SDI Regions (1990-2021).

	Globle		High SDI		High-middle SDI		middle SDI		low-middle SDI		low SDI	
	χ^2	P-Value	χ^2	P-Value	χ^2	P-Value	χ^2	P-Value	χ^2	P-Value	χ^2	P-Value
NetDrift = 0	25.29	＜0.01	4.57	0.03	90.97	＜0.01	1.06	0.30	8.35	＜0.01	5.62	0.02
All Age Deviations = 0	21381.47	＜0.01	11412.18	＜0.01	20951.53	＜0.01	26136.56	＜0.01	21353.52	＜0.01	23153.37	＜0.01
All Period Deviations = 0	8.17	1.00	3.39	1.00	23.38	0.80	9.94	1.00	1.76	1.00	6.61	1.00
All Cohort Deviations = 0	18.83	1.00	9.12	1.00	58.98	0.09	23.93	1.00	3.74	1.00	9.10	1.00
All Period RR = 1	41.01	0.11	10.01	1.00	140.14	＜0.01	10.04	1.00	10.85	1.00	11.08	1.00
All Cohort RR = 1	83.73	＜0.01	27.59	0.99	299.16	＜0.01	27.44	0.99	15.01	1.00	13.62	1.00
All Local Drifts = Net Drift	18.38	0.37	8.10	0.96	57.26	＜0.01	22.97	0.15	3.36	1.00	8.35	0.96

3.2. Joinpoint Regression Analysis of DALYs for ONHL (1990-2021)

As illustrated in Figure 1, the global DALY rate showed an overall upward trend, particularly with a sustained and significant increase from 1990 to 1997 (APC range: 0.36%-0.52%, P < 0.01), whereas the growth slowed markedly during 2019-2021 (APC = 0.01%, P > 0.05) (Figure 1A). In high-SDI regions, the DALY rate increased significantly during 1990-2005 and 2009-2019 (APC range: 0.20%-0.43%, P < 0.01), but declined significantly between 2005 and 2009 (APC = -0.33%, P < 0.01) (Figure 1B). In high-middle SDI regions, the DALY rate has shown a continuous upward trend since 1990, with particularly rapid increases observed during 2000-2005 and 2014-2019 (APC = 0.79% and 0.57%, respectively; both P < 0.01). A decreasing trend emerged in 2019-2021 (APC = -0.23%, P < 0.01) (Figure 1C). In middle-SDI regions, the DALY rate exhibited a fluctuating pattern. It increased significantly from 1990 to 1994, declined significantly from 1994 to 2001, rose again from 2001 to 2005, decreased from 2005 to 2015, increased again during 2015-2018, and declined once more from 2018 to 2021 (APC values of 0.23%, -0.08%, 0.18%, -0.10%, 0.14%, and 0.27%, respectively; all P < 0.01), indicating fluctuations and limited long-term control (Figure 1D).

In low-middle SDI regions, the DALY rate increased significantly from 1990 to 1998 (with an APC as high as 0.70% during 1990-1993, P < 0.01), then decreased thereafter. However, a renewed upward trend was observed in recent years (2019-2021; APC = 0.14%, P < 0.01), suggesting limited

effectiveness of current prevention and control efforts (Figure 1E). In low-SDI regions, the DALY rate declined significantly during 1990-1995 (APC = -0.33%, P < 0.01) but rebounded markedly between 1995 and 2000 (APC = 0.49%, P < 0.01), indicating a resurgence of disease burden. A significant decrease was seen from 2000 to 2019 (P < 0.01), followed by a sharp rebound during 2019-2021 (APC = 0.73%, P < 0.01) (Figure 1F).

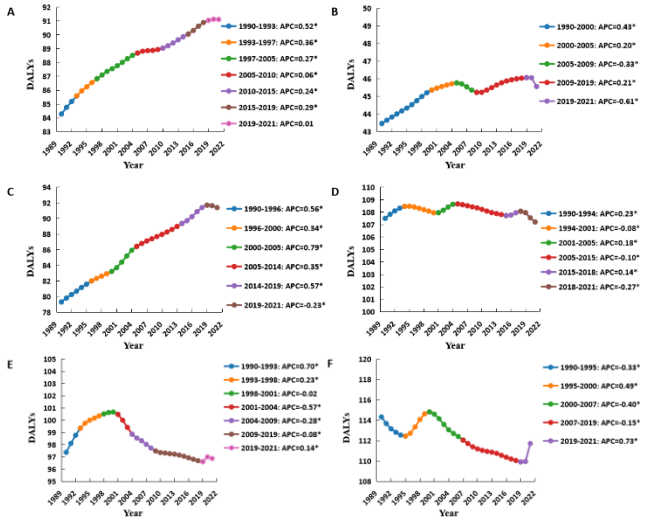


Fig.1 - Regression model for age-standardized DALYs rate (per 100,000) of ONHL across global (A), high SDI (B), high-middle SDI (C), Middle SDI (D), low-middle SDI (E), and low SDI regions (F). * Represents P<0.01. The figure was generated from the Joinpoint regression analysis of DALYs for ONHL. The colored dots represent DALYs value, different colour represent different Joinpoints. The APC of different Joinpoints are also shown.

3.3. Sex- and Age-Specific Burden of DALYs and SEV in 2021

As shown in Figure 2, across all SDI levels, DALYs increased with age, peaking at 50-54 or 60-64 years before declining, forming a typical "midlife peak." This pattern indicates a strong cumulative effect of occupational exposure. DALYs were consistently higher in males than in females, both in absolute numbers and age-specific rates, suggesting that men face greater occupational noise exposure and represent the primary high-risk group. High-SDI regions showed relatively low overall DALY levels with a flatter peak, indicating more effective protective measures (Figure 2B). In contrast, high-middle and middle-SDI regions had higher DALY levels, especially with a pronounced surge among males (Figures 2C and 2E). Although low-middle and low-SDI regions displayed lower overall DALY levels, their increase occurred earlier, with a broader and more prolonged peak. Notably, the peak in DALY counts typically occurred at ages 35-44, whereas the peak in DALY rates appeared 5-10 years later, further indicating a cumulative burden of disease over time.

As shown in Figure 3, substantial regional disparities in occupational noise exposure were observed across SDI categories. High-SDI regions had the lowest SEV (<18%), whereas lower SDI regions had progressively higher SEV, indicating poorer exposure control. In all regions, SEV increased with age and peaked in middle to older age groups, reflecting cumulative lifetime exposure. A clear gender gap in exposure was observed across SDI levels, with males showing significantly higher SEV than females, particularly between the ages of 40 and 69. However, in low-SDI regions, SEV among females also rose markedly, suggesting that women in these regions are frequently engaged in noisy work environments. Overall, exposure control and protective measures appear more effective in high-SDI settings, whereas low and low-middle SDI regions still experience high levels of chronic exposure over extended periods.

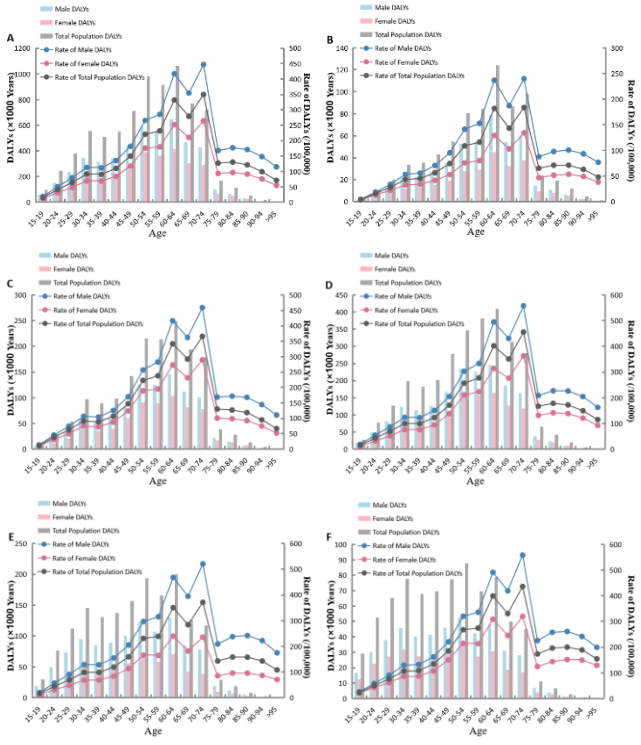
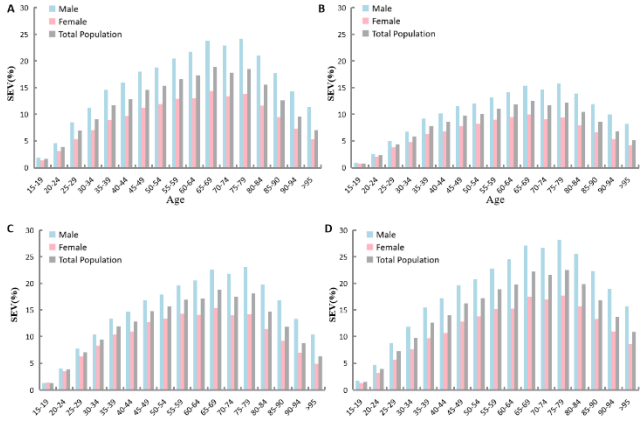


Fig. 2 - DALYs value and DALY rates of ONHL across global (A), high SDI (B), high-middle SDI (C), Middle SDI (D), low-middle SDI (E), and low SDI (F) regions, 2021. The bars represent the DALY values, while the line graph corresponds to the DALY rates. Different colors indicate males, females, and both sexes, respectively.



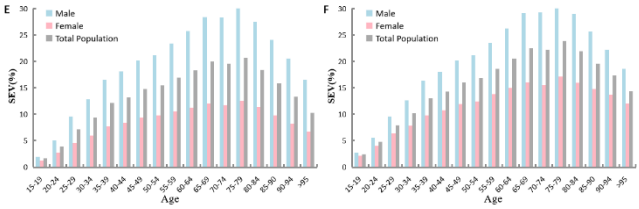


Fig. 3 - SEV of ONHL across global (A), high SDI (B), high-middle SDI (C), Middle SDI (D), low-middle SDI (E), and low SDI (F) regions, 2021. Different colors indicate males, females, and both sexes, respectively.

3.4. Age-Period-Cohort Analysis of DALYs and SEV

From 1990 to 2021, the net drifts of DALYs showed increasing trends globally and in high- and high-middle SDI regions, with values of 0.23% (95% CI: 0.14%, 0.32%), 0.14% (95% CI: 0.01%, 0.27%), and 0.45% (95% CI: 0.36%, 0.54%), respectively. In contrast, DALYs declined in middle-, low-middle-, and low-SDI regions, with net drift values of -0.04% (95% CI: -0.12%, 0.04%), -0.12% (95% CI: -0.21%, -0.04%), and -0.09% (95% CI: -0.17%, -0.02%) (Figure 4). These trends were highly significant on the global level and in high-middle and low-middle SDI regions ($P < 0.01$), significant in high- and low-SDI regions ($P < 0.05$), but not statistically significant in middle-SDI regions ($P = 0.30$, Table 2).

Results from the APC model (Table 2) revealed that age deviations were highly significant ($P < 0.01$) across all SDI strata, indicating marked differences between age groups. A significant period effect was observed only in high-middle SDI regions (χ^2=140.14, $P < 0.01$), while period effects in other regions were not statistically significant ($P > 0.05$) (Figure S1). Cohort effects were highly significant globally and in high-middle SDI regions (both $P < 0.01$), but were not significant in the remaining SDI groups ($P > 0.05$) (Figure S2). For SEV, the APC model similarly showed highly significant age deviations in all SDI regions ($P < 0.01$), suggesting notable differences in exposure levels across age groups. However, neither period nor cohort effects were statistically significant across all SDI strata (all $P > 0.05$) (Table S1, Figures S3-S5).

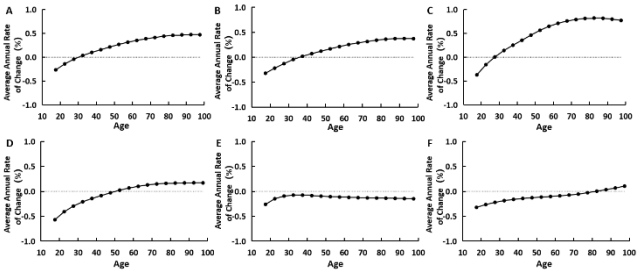


Fig.4 - Local drift with Net drift across (A) global; (B) High SDI region; (C) High-middle SDI region; (D) Middle SDI region (E) Low-middle SDI region; (F) Low SDI region.

3.5. ARIMA Model Projections (2025-2035)

With the ARIMA model, we forecasted DALYs values, DALYs rates and SEV of ONHL from 2025 to 2035. The model indicates that DALYs across age groups will experience new fluctuations over the next decade, while SEV will experience little change (Figure 5). By 2035, the global total DALYs attributable to occupational noise are projected to reach 9.65 million person-years, with a DALY rate of 2,477 per 100,000 person-years (Figure 5A, 5B). The age group 55-59 years is expected to have the highest contribution to total DALYs, whereas the highest DALY rate will occur in the 70-74 years age group. Compared with 2021, the global total DALYs are predicted to increase by 22.97% by 2035. Notably, among individuals aged 55-59 years, DALY counts are projected to grow rapidly in the next decade. In contrast, DALYs among those under 50 years of age may stabilize, entering a plateau phase (Figure 5A).

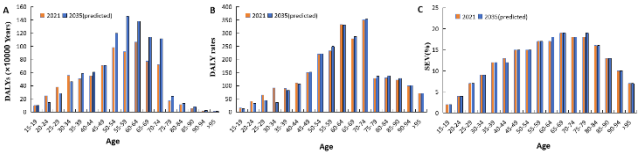


Fig. 5 - Predicted DALYs (A), DALY rates (B) and SEV (C) of ONHL in 2021 and 2035 (global). Different colors indicate different year.

4. Discussion

This study provides a comprehensive assessment of the global, regional, and demographic burden of ONHL from 1990 to 2021, using the Global Burden of Disease (GBD) data, and projects future trends to 2035 through ARIMA modeling. Our findings reveal a persistent global increase in ONHL burden over the past three decades, with pronounced disparities across Socio-demographic Index (SDI) regions, sex, and age groups. These results underscore the urgent need for enhanced global strategies to prevent occupational noise exposure, particularly in low- and middle-SDI countries.

Our analysis shows that global DALYs due to occupational noise increased by over 100% from 1990 to 2021, in line with prior reports indicating that occupational noise exposure remains a leading contributor to adult-onset hearing loss worldwide [3][4][5]. Despite regulatory frameworks and hearing conservation programs in many countries, the effectiveness of implementation varies widely [8][9]. High-SDI regions, while maintaining relatively lower DALY rates, showed stable or slightly rising trends, suggesting persistent residual exposure in certain industries or populations. Meanwhile, low-SDI and low-middle-SDI regions experienced earlier onset, broader peaks, and higher growth in DALYs, possibly reflecting rapid industrialization, lack of regulatory enforcement, and poor access to hearing protection devices [12][13].

The observed sex-based disparities are notable, males consistently bore a higher burden of ONHL across all regions. This finding aligns with prior studies attributing this disparity to higher male employment in noise-intensive occupations such as construction, manufacturing, and mining [3][14]. However, the rising SEV among females in low-SDI regions may indicate growing female labor participation in informal or unregulated sectors with inadequate noise controls [15].

Age-specific trends also support the notion of cumulative exposure, with DALY counts peaking in midlife (35-59 years) and DALY rates peaking later (60-74 years). This reflects the latency and progressive nature of hearing loss due to chronic noise exposure, a phenomenon supported by

auditory pathology studies demonstrating gradual cochlear and neural damage even in the absence of acute symptoms [16]. These patterns highlight the importance of early detection and preventive interventions beginning early in the workforce lifecycle.

The Age-Period-Cohort (APC) analysis reinforces the significance of age as a dominant risk factor, with less consistent evidence for period and cohort effects, except in high-middle SDI regions. This may suggest that ONHL risk is more influenced by cumulative biological vulnerability and occupational tenure than by short-term policy shifts or generational changes. The absence of strong period effects in most regions also reflects the inadequacy of policy-level interventions in meaningfully altering exposure patterns at a population scale [3].

Importantly, our ARIMA projections suggest that the global DALY burden of ONHL will continue rising, reaching nearly 9.65 million person-years by 2035. Notably, the most substantial increases are expected among individuals aged 55-59 years, likely reflecting both aging workforces and historical exposure lag. These projections echo prior modeling studies on the global burden of non-communicable auditory diseases [11], and suggest that ONHL may increasingly strain health systems, particularly in low-resource settings.

From a public health perspective, our findings have significant implications. The persistence and projected growth of ONHL call for urgent integration of occupational noise reduction into national hearing action plans, aligned with the WHO's World Report on Hearing [17]. Engineering controls, stronger regulatory compliance, personal protective equipment distribution, and periodic audiometric screening are cost-effective and evidence-based strategies [18][19]. Moreover, exposure surveillance and enforcement should particularly target informal sectors and high-risk demographic groups, including aging male workers and underserved female laborers.

Key strengths of this study include the use of standardized GBD data across a 30-year timespan and multiple analytical frameworks (Joinpoint, APC, ARIMA), allowing robust temporal and demographic comparisons. However, several limitations should be acknowledged. First, GBD estimates rely on model-based extrapolations and may underrepresent ONHL in regions lacking occupational health data. Second, our analysis focuses on DALYs and SEV without incorporating economic or psychosocial impacts of hearing loss. Third, occupational noise was assessed as a singular risk factor, although synergistic exposures (e.g., solvents, ototoxic medications) are also relevant but were not analyzed [20].

5. Conclusion

ONHL remains a persistent and rising global health burden, particularly in lower-SDI regions and among aging male populations. Targeted, equitable prevention and surveillance strategies are essential to mitigate the projected increase in disease burden. Enhanced policy commitment, investment in protective technologies, and integration of hearing conservation into occupational health systems will be critical to reversing current trends.

Declaration

A.1. Authors' contributions

Jun Yang and Bing Xu designed the research; Hong Chen performed the research and analyzed the data; Jun Yang and Bing Xu wrote the paper.

A.2. Conflict of Interest

The authors declare that they have no competing interests.

A.3. Data Availability Statement

The datasets generated and/or analysed during the current study are availablein the [Global Health Data Exchange GBD Results Tool] repository, [http://ghdx.healthdata.org/gbd-results-tool].

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