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The Dose Response Relationship between In Ear Occupational Noise Exposure and Hearing Loss

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Abstract

Objectives—Current understanding of the dose-response relationship between occupational noise and hearing loss is based on cross-sectional studies prior to the widespread use hearing

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Competing Interest

Two of the authors (DG and PMR) provide consulting services to Alcoa Inc as part of a service agreement. One of the authors (CDE) serves as the Alcoa corporate audiologist.

Data Sharing:

Each of the investigators and collaborating Institutions is committed to the principle of making data and analyses as transparent and available as possible to colleagues and other investigators, as the best way to maximize the scientific value of our work. That said, some of the data used for the proposed analyses derives directly from data transferred to Stanford and Yale under a longstanding contract with Alcoa that precludes access to investigators not covered under the agreement, and precludes the undertaking of analyses or topics not sanctioned by the Company (while fully protecting all academic prerogatives once a project, such as this one, has been approved). The reason for these restrictions is that some sets contain easily accessible Company-sensitive and proprietary data within them, including, but not limited to: detailed Company labor practices, Company production and other economic indicators, proprietary technical and production process information, and data relevant to sensitive social issues. None of these could be fully protected, nor could individual identities in theory, even with individual identifiers redacted, given the richness of the data. For example, the identity of employees could be reconstructed by linking age, date of employment, location, job title, salary, periods of lost work, health and injury claim information, without recourse to specific identifiers.

As an alternative to providing a de-identified data set to the public domain, we allow access for the purpose of re-analyses or appropriate “follow-on” analyses by any qualified investigator willing to sign a contractual covenant with the host Institution limiting use of data to a specific agreed upon purpose and observing the same restrictions as are limited in our contract with Alcoa, such as 60-day manuscript review for compliance purposes.

Contributorship

PMR and CDE conceived the paper, with input from RN, JC, and DG. DG performed analysis of data. PMR, RN, and JC drafted the manuscript and CDE and DG assisted with revisions. All authors reviewed and approved final version.

protection and with limited data regarding noise exposures below 85dBA. We report on the hearing loss experience of a unique cohort of industrial workers with daily monitoring of noise inside of hearing protection devices.

Methods—At an industrial facility, workers exhibiting accelerated hearing loss were enrolled in a mandatory program to monitor daily noise exposures inside of hearing protection. We compared these noise measurements (as time-weighted L_{AVG}) to interval rates of high frequency hearing loss over a six year period using a mixed effects model, adjusting for potential confounders.

Results—Workers' high frequency hearing levels at study inception averaged more than 40 dB hearing threshold level (HTL). Most noise exposures were less than 85dBA (mean L_{AVG} 76 dBA, interquartile range 74 to 80 dBA). We found no statistical relationship between LAvg and high frequency hearing loss (p = 0.53). Using a metric for monthly maximum noise exposure did not improve model fit.

Conclusion—At-ear noise exposures below 85dBA did not show an association with risk of high frequency hearing loss among workers with substantial past noise exposure and hearing loss at baseline. Therefore, effective noise control to below 85dBA may lead to significant reduction in occupational hearing loss risk in such individuals. Further research is needed on the dose response relationship of noise and hearing loss in individuals with normal hearing and little prior noise exposure.

Keywords

Hearing loss; Noise induced; Dose response

BACKGROUND

An ongoing debate in the hearing conservation literature is the true damage-risk relationship between noise exposure and acquired sensorineural (noise-induced) hearing loss. Better elucidating this relationship is necessary towards establishing effective standards for noise control and hearing conservation efforts. At present, there is disagreement about what constitutes a "safe" level of occupational noise exposure. The Occupational Safety and Health Administration (OSHA) sets the permissible noise exposure level at 90 dBA for an 8-hr time-weighted average (TWA) using a 5-dB exchange rate (the change in average noise level associated with a halving or doubling of allowable exposure duration), with an action level requiring hearing conservation programs at 85 dBA,[1] National Institute for Occupational Safety and Health (NIOSH) recommends an 85-dBA exposure limit, time-weighted using a 3-dB exchange rate[2]. To make these critical decisions about the allowable levels of noise exposure for workers, improved understanding of the dose-response relationship between in-ear noise and hearing loss is needed.

The current regulatory levels for occupational noise exposure were based on cross-sectional studies performed before the widespread adoption of hearing conservation programs. These prior studies suffered a number of shortcomings, including the variable use of hearing protection by study subjects, fairly crude assessment of ambient noise exposure levels, and the limitations of hearing assessed at only one point in time. Most of these studies had limited or no data to address the effects of noise exposures below 85dBA. In addition, many of the studies were done before hearing protection use was widespread in industry. A 1997 study of the NIOSH Occupational Noise and Hearing Survey (ONHS), for example, estimated that the excess risk of incurring material hearing impairment (defined as an average binaural average hearing level at 0.5, 1, and 2 KHz in excess of 25dB) was 15% and 3% for lifetime working exposures to 85 and 80dBA, respectively, but noted that insufficient data for workers with average daily exposures less than 85dBA led to variability in risk estimates. The study recommended that: "new data collection efforts should focus on better characterization of dose-response and longitudinal hearing surveys that include workers exposed to 8-hour time-weighted average noise levels below 85 dB."[3] The US Environmental Protection Agency suggests below 8-hour time-weighted average noise levels of 75 dBA no hearing loss would be expected in any individual at any audiometric test frequency.[4]

Since the introduction of the OSHA standard, it has been difficult to revisit the damage-risk relationship between noise and hearing loss, as NIOSH has noted; "the prolific use of hearing protectors in the United States since the early 1980s would confound the determination of dose-response relationships for occupational noise-induced hearing loss (NIHL) among contemporary workers." [5]

In modeling the dose-response relationship between noise and hearing loss, one important issue is the effect of brief but intense exposures, as some evidence indicates that such "impulsive" noise is more damaging to hearing than steady noise.[6] Seixas and colleagues developed[7] and validated [8] metrics for impulsive noise by measuring both the maximum noise levels during a workshift (L_{max}), and also dividing that number by the time weighted average noise exposure (L_{eq}). This new metric (L_{max}/L_{eq}), was an attempt to capture the impulsiveness or "peakiness" of the noise exposure. There is a need to further explore whether such innovative metrics allow for greater ability to model dose-response relationships between noise and hearing loss.

To address these knowledge gaps, we examined a unique cohort of industrial workers enrolled in a program of daily monitoring of noise dose inside the ear, inside hearing protective devices, enabling a unique examination of the dose-response relationship for noise exposures below 85 dBA and hearing loss risk.

METHODS

We studied the hearing loss experience of workers in an aluminum production facility that were enrolled in both the company's hearing conservation program as well as a mandatory program of daily noise exposure monitoring. The daily exposure monitoring is mandatory for individuals who had exhibited an audiometric "shift" from baseline of at least 5 dB in the average of 2, 3, and 4 KHz, in either ear. We have previously reported on this program.[9] Once placed in the program, workers are expected to remain in it for the duration of their employment. As part of this program, workers wear a dosimeter (QuietDose ®, Sperian Inc. San Diego CA) that records, through a microphone fitted inside of earplugs or earmuffs, the daily "in-ear" noise exposure. At the end of each work shift, the worker downloads the exposure data into a computer database by means of an infrared reading device. At that time, the worker is notified of the time-weighted average noise "dose" (percentage of the 90-dBA permissible exposure limits (PEL)). The exposure data is also available through the database to plant management, and an automatic notice is generated if the noise exposure exceeds 100% dose. The dosimeter settings resembled traditional noise dosimetry for the purpose of OSHA compliance (80dBA threshold and 90dBA Exposure Limit, time weighted average calculated with a 5-dB exchange rate). Workers also undergo audiometric testing yearly and complete an annual audiometric questionnaire as part of the hearing conservation program.

Through an ongoing research relationship between Alcoa Inc. and the Yale School of Medicine, protocols for analysis of de-identified data sets have been developed and approved by the Human Investigation Committee of the Yale School of Medicine. Using these de-identified data sets, we studied the noise exposures and the audiograms and annual hearing questionnaires of workers in the mandatory daily noise exposure monitoring program. Among these workers, we selected 107 individuals who had had at least three audiograms over at least three years since beginning daily exposure monitoring. For each individual, we used the change in hearing levels between each of their contiguous audiogram results to calculate an annualized rate of hearing loss (in dB/year). We then used the individual's daily noise exposure measurements between these audiograms to calculate the time weighted average of noise exposure. The 107 individuals in the study contributed a total of 538 paired audiometric intervals that were used in the analysis. We assessed the annualized rate of hearing loss for individual frequencies between 500 and 8000 Hz as well as for the binaural average of the noise-sensitive frequencies of 2,3,4 KHz and 3, 4, and 6 KHz.

To assess the association between individual hearing loss and noise exposures we calculated several noise exposure metrics, including L_{AVG} (time-weighted average of all recorded noise exposures over the interval) and Monthly Maximum $L_{AVG\_}$ (time-weighted average of the highest monthly L_{AVG} noise exposure over the interval), which may be treated as an upper bound of typical daily noise exposures. Exposure to non-occupational noise was assessed through individual responses on the annual hearing questionnaire, which asked about hunting and shooting and "other noisy hobbies".

We developed a linear mixed effects model that considered the use of these multiple hearing loss and noise exposure measures per subject over time to assess hearing change and its relationship to noise exposure over the same period, adjusting for the subject-specific fixed effects age, race, baseline hearing level, and non-occupational noise exposure. All models included random intercepts for subjects to control for the non-independence of the subjects multiple measurements. Independent variables with no significant association with the rate of hearing loss ($p > 0.05$) were removed from the final multivariate models to simplify the results. Since L_{AVG} and Monthly Maximum L_{AVG} were highly correlated we developed two separate models for each. All statistical analyses were performed using the SAS system software (SAS Institute Inc., Cary, NC, USA). Linear mixed models were estimated using the PROC MIXED procedure.

RESULTS

Demographic characteristics for the study population are summarized in Table 1. Of the 107 individuals (all but one male) with at least three audiograms since beginning participation in the mandatory monitoring program, the average age was 50 years (SD = 7.2 years), and the average duration of employment was 23.7 years (SD = 9.9 years). The majority (87.9%) was Caucasian, and almost 40% reported a history of hunting or shooting activities on their audiometric questionnaire. The average high frequency hearing levels (average of 3,4, and 6kHz) for the study participants was greater than 40dB, indicating a significant degree of baseline hearing loss.

Noise Exposures

Table 2 shows the time weighted average (L_{AVG}) and the time-weighted average of the monthly maximum (Monthly Maximum L_{AVG}) noise exposure measurements recorded between 2 audiograms. These two metrics were highly correlated ($\rho = 0.92$).

Relationship between noise exposures and hearing loss risk

Figure 1 shows the relationship between L_{AVG} and annualized rates of hearing loss between audiograms at the higher frequencies of 3,4, and 6KHz. The scatter plot suggests that there is no significant relationship between noise exposure level and rate of hearing loss.

Results of Mixed Model

In the mixed model, increasing age was the only statistically significant predictor on the rate of hearing loss. Noise exposure metrics L_{AVG} and Monthly Maximum L_{AVG} did not show any association with hearing loss at the average of the noise sensitive frequencies 3, 4, and 6KHz (Table 3). We performed subanalyses to see whether looking at individual frequencies, or the combined frequencies of 2,3,4 KHz altered the findings, but again found no significant effect of noise exposure level on hearing loss risk. Since the duration of workshifts varied, we also adjusted for hours worked in the model and did not find a significant effect.

DISCUSSION

This study examines a unique occupational dataset of daily in-ear noise dose measures and audiometry data, enabling an unprecedented examination of the dose response relationship between noise (measured “at ear”) and hearing loss in an occupational environment, where uneven use of hearing protection can powerfully modify observed associations between ambient noise levels and actual noise exposures inside of hearing protectors. Over the time period of observation, we were unable to detect a clear dose-response relationship between recorded daily levels of occupational noise exposure inside of hearing protectors, which were usually well below 85dBA, and annual rate of high frequency hearing loss. We also were unable to show an effect of the highest daily average noise exposure for individuals. On the other hand, increasing age was associated with a greater risk for hearing loss over time.

One possible implication of these findings is that hearing conservation programs that control actual noise exposures to less than 85dBA (the current OSHA action level) may be able to significantly limit the amount of occupational hearing loss in noise-exposed workers. In fact, we have reported that the regular use of the monitoring device appears to reduce the risk of hearing loss over time [9]. However there are a number of reasons to approach these findings with caution. The dosimeters were set to an 80dB noise "floor" or threshold (a conventional setting for industrial noise measurements), meaning that exposures at levels less than 80dBA were not directly recorded. Due to the logarithmic nature of the decibel scale, such exposures would have contributed only minimally to the recorded "dose" expressed as a percentage of the OSHA PEL (90dBA for an 8 hour average). However, future studies, using dosimeters set to a lower noise "floor", could further elucidate the dose response relationship at low noise exposure levels. The dosimeters used a conventional 5 dB "exchange" to calculate noise dose over a work shift; some authorities have recommended the use of a 3dB exchange rate, which over the range of exposures seen in this study would tend to produce higher estimates of noise exposure levels. Future studies should also explore the impact of a 3dB exchange rate on the noise-hearing loss dose response relationship. This study relied on measurements of noise exposures inside of hearing protection rather than traditional dosimetry measurements of ambient (at shoulder) noise exposure. Due to ear canal resonance, there may be differences between at ear noise exposure levels and ambient noise measurements, with the at ear noise exposure levels ranging from 2–4 dB higher than the corresponding ambient level[10]. Therefore, it is possible that a subtle effect of low level noise exposure on hearing loss risk could be obscured by this exposure misclassification.

The current dosimeter technology used to measure at ear noise exposures in this study did not record a detailed dosimetry log data to assess the possible effects of peak noise exposures within the workday. Consequently, while we did not find a relationship between monthly maximum daily noise exposure and hearing loss, it is possible that short term peak exposures during a workday could have an effect on hearing loss that we were unable to estimate. Worker responses to an audiometric questionnaire regarding hunting and shooting activities or noisy hobbies did show a relationship with hearing loss. In other studies, recreational use of guns and other non-occupational noise exposure have been associated with hearing loss [11,12]. As such, unmeasured non-occupational exposures may confound observed dose-response relationships, and bias them to the null.

The data set is an existing data set of noise exposures gathered for administrative purposes related to the conduct of the hearing conservation program at the industrial facility. The program is mandatory, and individuals who exhibit overexposures to noise receive increased scrutiny from supervisors in an effort to reduce further overexposures. It is therefore possible that some participants could be underreporting noise exposures (through actions such as not accurately recording exposures by disconnecting microphones, etc.) in order to avoid administrative consequences. While we could not determine this directly, we did find that approximately 10% of the noise exposure measurements were 0% of the PEL. Excluding these values did not change our findings.

We detected no significant effect of average maximum monthly noise exposures on hearing loss. This result does not rule out an effect of impulsive noise exposure or noise "peakiness".

The dosimeters used by the workers were capable of storing only the daily time-weighted average exposure, and did not capture short term exposure peaks. Further research with daily in ear noise monitoring including logging dosimetry of short-term noise exposure peaks would be useful. Additionally, we were unable to detect an effect of hours worked on hearing loss. This supports the validity of the use of time weighted average noise exposures, across varying shift lengths, to determine hearing loss risk, although further examination of this issue is also warranted.

One possible effect in a longitudinal study of hearing loss is "regression to the mean", whereby individuals with worse hearing at baseline exhibit less hearing loss over the subsequent observation period due simply to random test error that regresses to the mean with repeated measurements. We have previously noted that this could explain in part the observation that rates of hearing loss declined in workers performing the daily noise monitoring after being selected for the mandatory monitoring program. This phenomenon could also make it difficult to detect a dose response relationship.

Prior hearing loss and reduced cochlear hair cells may explain the observed lower rate of hearing loss among individuals with worse baseline hearing. Indeed, other studies have suggested a decelerating risk of noise-induced hearing loss after 10–15 years of exposure[13]. The subjects in our study had average high frequency hearing thresholds of greater than 40dB, consistent with moderate hearing loss and hearing impairment at these frequencies at baseline. In fact, there is evidence that suggests that the workers in this study may have effectively reached a plateau of hearing loss for their exposure levels. Prince and colleagues analyzed noise levels and hearing damage from the Occupational Noise and Hearing Survey (ONHS) conducted by the National Institute for Occupational Safety and Health.[3] Prince et al found hearing thresholds at 3, 4, and 6 kHz that were very consistent with those seen in the current study among ONHS workers aged 44–50 years old, with a nearly identical tenure to the subjects in the current study, and with 88–92 dBA ambient noise exposures. Considering that many hearing protectors provide attenuation in the range of 10–20 dB,[14] it seems likely that the ambient exposures of the subjects in this study were in the 85–95 dBA range. Workers in the next oldest ONHS age group (51–71 years old) had hearing threshold levels that were very similar to those in the 44–50 year old group, suggesting that additional exposure at these levels did not produce additional hearing damage. These data, and those collected in the current study, demonstrate the need for similar dose response investigations in younger individuals with better baseline hearing and more potential hearing to lose over the follow-up period.

Along a similar line, some individuals in the study showed an actual improvement in hearing thresholds over the study period. The reasons for this remain unclear, since noise induced hearing loss is considered a permanent condition due to the irreversible loss of cochlear hair cells. However, since workers in hearing conservation programs receive annual audiometry during work shifts, they may experience temporary elevation of hearing thresholds ("temporary threshold shift") during work shifts. Therefore, temporary shifts at the beginning of the study period could have influenced the subsequent slope of hearing loss during the period of observation. Measurement uncertainty in periodic industrial audiometric testing could also explain some of the fluctuation in hearing threshold levels.

The study population overall exhibited significant high frequency hearing loss at the beginning of the observation period. While this population resembles many working populations in the U.S. and other industrialized countries, it may be less representative of working populations in developing countries where much heavy manufacturing currently takes place. Since noise induced hearing loss is believed to be greatest during the first 10–15 years of occupational noise exposure,[8] the dose response relationship may differ for younger individuals with lesser hearing loss at baseline, as suggested above. At the same time, our subanalysis of the 25% of individuals in the cohort who had thresholds of 30dB or better for the average of frequencies 3,4, and 6KHz at baseline did not show a significant dose response. Additional, larger studies would be useful to confirm these findings. Also, studies where a greater fraction of subjects are exposed between 80 and 85 dBA are needed; a large fraction of our subjects who showed no change in hearing over time had protected noise levels low enough (e.g., at or below an 8-hour time-weighted average of 75 dBA) to have minimal or no risk of noise induced hearing damage. [4]

Further study of in-ear noise exposures between 80 and 85dBA over longer observation periods could have important implications for industrial hearing conservation. Other noise exposure guidelines set lower exposure action level for ambient noise exposures to as low as 80dBA [15] and use a 3dB exchange rate for time-averaging of exposures. At the same time, overuse of hearing protection at lower noise levels may interfere with speech communication and safety[16] without providing significant health benefits. Identifying proper regulatory levels for noise exposure, including outcome-based comparisons of measurements using either a 3dB or a 5dB exchange rate, could lead to enhanced and optimal prevention of noise-induced hearing loss.

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WHAT THIS PAPER ADDS

Contemporary attempts to assess the dose response relationship between occupational noise exposure and hearing loss risk have been confounded by the fact that workers are using hearing protective devices. This study makes use of a unique technology capable of measuring noise exposures inside of hearing protection on a continuous basis, and compares these noise exposures to the hearing loss experienced by the worker over several years. This novel approach sheds valuable new light on the dose response relationship between noise and hearing loss, with implications for regulation and practice.

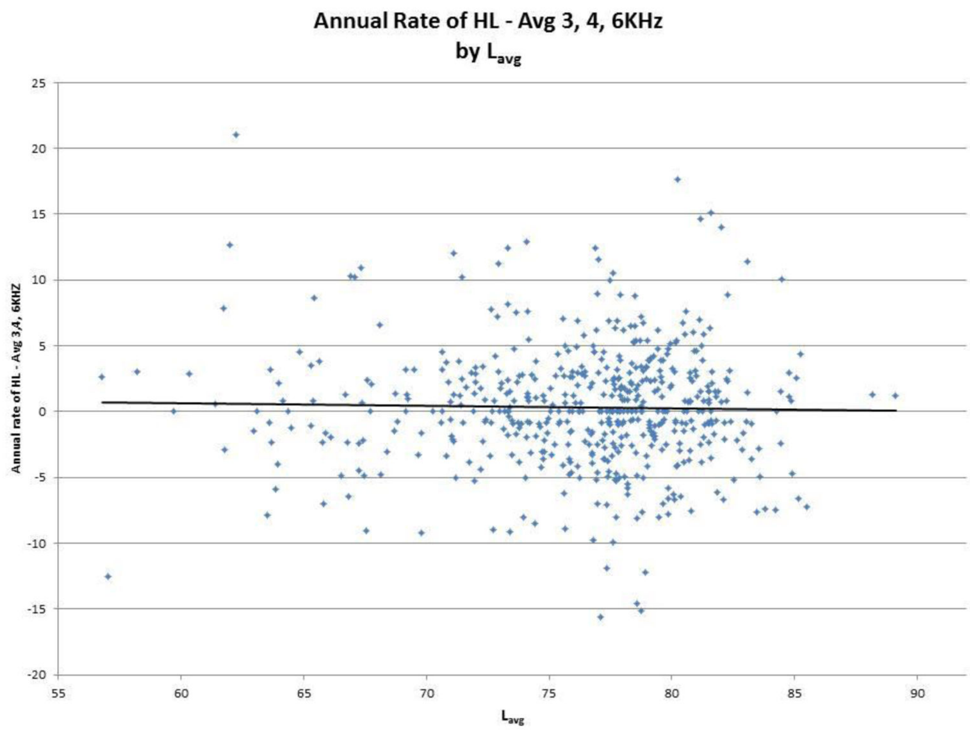

Figure 1.

Relationship between Noise Exposure (L_{AVG}) and Rate of Hearing Loss (dB/yr) Rate of Hearing Loss (dB/yr)

Table 1

Subject Characteristics (N=107)

Characteristic	
Age (mean, sd)	49.8 (7.2)
Male (n,%)	106 (99.1)
Race (n,%)	
White	94 (87.9)
Hispanic	8 (7.5)
American Indian/Alaska native	4 (3.7)
Asian	1 (0.9)
African American	0 (0.0)
Tenure (years: mean, sd)	23.7 (9.9)
History of Shooting (n,%)	40 (37.4)
Noisy Hobby (n,%)	57 (53.3)
Hearing at beginning of intervention- avg 3,4,6KHz (mean, sd)	42.6 (17.7)
Number of Audiograms (mean, sd)	5.0 (1.1)

Table 2

Distribution of L_{AVG} (time-weighted average of daily noise exposures) and Monthly Maximum L_{AVG} (time-weighted average of monthly maximum noise exposure)

	N	Mean	Median	Q1 (25th Pctile)	Q3 (75th Pctile)	Min	Max
Noise Exposure							
L_{AVG}	538	76.3	77.5	73.7	79.6	56.8	89.1
Monthly Maximum L_{AVG}	538	82.5	83.3	80.7	85.1	56.8	95.7
Hearing Loss							
Change in average 3,4.6KHz (dB/year)	538	0.34	0.0	−2.2	2.7	−15.6	21.0

Table 3

Predictors of the Annual Rate of Hearing Loss in Average of 3, 4, and 6 KHz, using either L_{AVG} or Monthly Maximum L_{AVG} as noise exposure variables

Variable	Bivariate (unadjusted)		Using L_{AVG} Multivariate (adjusted)		Using Monthly Maximum L_{AVG} Multivariate (adjusted)	
	Estimate (SE)	p-value	Estimate (SE)	p-value	Estimate (SE)	p-value
intercept			−0.52 (2.47)	0.834	0.42 (3.13)	0.8943
age	0.04 (0.02)	0.033	0.04 (0.02)	0.0335	0.04 (0.02)	0.0382
race	0.24 (0.43)	0.578				
Tenure	0.02 (0.01)	0.095				
History of shooting	0.05 (0.29)	0.875				
Noisy hobby	−0.19 (0.28)	0.504				
Hearing at start of interval avg 3,4,6KHz	−0.01 (0.01)	0.441				
L_{AVG}	−0.02 (0.03)	0.545	−0.02 (0.03)	0.5317		
Monthly Maximum L_{AVG}	−0.03 (0.04)	0.364			−0.03 (0.03)	0.4295