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Linda F. Cantley, Deron Galusha, and Martin D. Slade

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Early hearing slope as a predictor of subsequent hearing trajectory in a noise-exposed occupational cohort

Linda F. Cantley,[a)] Deron Galusha, and Martin D. Slade
Yale Occupational and Environmental Medicine Program, Yale University School of Medicine, New Haven, Connecticut 06510, USA

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Variations in individual susceptibility to noise-induced hearing loss have been observed among workers exposed to similar ambient noise levels but the reasons for this observation are poorly understood. Many workers are exposed to hazardous levels of occupational noise throughout their entire careers. Therefore, a mechanism to identify workers at risk for accelerated hearing loss early in their career may offer a time-sensitive window for targeted intervention. Using available longitudinal data for an occupationally noise-exposed cohort of manufacturing workers, this study aims to examine whether change in an individual's high frequency hearing level during the initial years of occupational noise exposure can predict subsequent high frequency hearing loss. General linear mixed modeling was used to model later hearing slope in the worse ear for the combined frequencies of 3, 4, and 6 kHz as a function of early hearing slope in the worse ear, age at baseline, sex, race/ethnicity, mean ambient workplace noise exposure, and self-reported non-occupational noise exposure. Those with accelerated early hearing loss were more likely to experience a greater rate of subsequent hearing loss, thus offering a potentially important opportunity for meaningful intervention among those at greatest risk of future hearing loss.
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I. INTRODUCTION

Although estimates for the prevalence of hearing loss in the United States (U.S.) vary widely depending upon data and methods used, an analysis of data from the 2001–2008 cycles of the National Health and Nutritional Examination Surveys (NHANES) (Lin *et al.*, 2011) estimated that 30×10^6 or 12.7% of Americans aged 12 years and older have bilateral hearing loss as defined by the World Health Organization (WHO) criteria (WHO, 2011) for hearing loss.

Globally, approximately 16% of disabling hearing loss in adults (Nelson *et al.*, 2005) and over 4×10^6 disability adjusted life years (DALYs) (WHO, 2002) are attributable to occupational noise. The costs associated with hearing loss include the financial burden resulting from lower employment rates and lower wages among individuals with hearing loss compared to those with normal hearing as well as the myriad but less clearly defined costs associated with quality of life reductions among those suffering hearing decrements (Neitzel *et al.*, 2017). In some instances, hearing impaired workers may require job re-assignment or suffer job loss (Ologe *et al.*, 2006; Jennings and Shaw, 2008). Of great concern for aging adults is evidence suggesting that communication impairments resulting from hearing loss can lead to social isolation and increase risk of chronic disease, including depression (Genther *et al.*, 2014) as well as other evidence suggesting that hearing loss may adversely affect cognitive load (Martini *et al.*, 2014). With hearing loss, auditory perception becomes more difficult, and may require dedication of greater cognitive resources to auditory perceptual processing to the detriment of critical processes such as working memory.

In 1983, the Occupational Safety and Health Administration (OSHA) mandated workplace hearing conservation programs with the purpose of substantially reducing occupational hearing loss (OSHA, 1983). Since the incorporation of this standard, various approaches have been undertaken to reduce noise-induced hearing loss (NIHL) including engineering controls to reduce the ambient noise levels, requiring the use of various types of hearing protection devices (HPDs), implementing administrative controls to reduce the time employees spend in high noise areas, and employee educational programs pertaining to noise exposure and hearing health. Despite these efforts, occupational NIHL remains a substantial problem with some evidence suggesting that certain work environments are getting louder (Aubert and McKinley, 2011). Other reports provide evidence of decreasing noise exposure levels over the past few decades, particularly in the manufacturing sector (Sayler *et al.*, 2019), though the prevalence of NIHL remains high in the manufacturing as well as other sectors.

Well-established factors contributing to an individual's risk of hearing loss include occupational and non-occupational noise exposure, exposure to ototoxicants, trauma, adverse health conditions, as well as race, age, and gender (Humes, 1984; Henderson *et al.*, 1993; Themann *et al.*, 2015). Unlike hearing loss due to aging, which continues to accelerate over time, NIHL typically increases most swiftly during the initial 10 to 15 years of exposure (Mirza *et al.*, 2018) after which the rate of loss slows. More poorly understood but of particular

[a)]Electronic mail: linda.cantley@yale.edu

interest are the apparent variations in individual susceptibility to NIHL observed among workers exposed to similar ambient noise levels (Stucken and Hong, 2014). Because many workers are exposed to hazardous levels of occupational noise throughout their entire career, identifying those at risk for accelerated hearing loss during the early years of working in noise may offer an opportunity for targeted intervention to reduce the projected rate of hearing loss likely to occur, particularly in the first decade and a half of exposure.

Taking advantage of existing longitudinal data for a occupationally noise-exposed cohort of light and specialty metals workers from a single corporation, the aim of this quantitative study is to examine whether change in an individual's hearing level during the initial years of occupational noise exposure can predict subsequent hearing loss among a continuously exposed cohort of workers. The study cohort was comprised of workers enrolled in the study company's hearing conservation program who worked in jobs for which noise sampling data were available, and who underwent annual audiometric testing for each year they held a noise-exposed job. Company policy mandated the use of hearing protection at all times while working in noise. Interestingly, previous research on this cohort found that workers exposed to higher ambient noise levels suffered less hearing loss than those exposed to lower levels of noise, indicating that ambient noise exposure alone may be a poor predictor of hearing loss (Rabinowitz *et al.*, 2007). Consequently, for this cohort as well as other groups of long-term workers in noise-exposed occupational settings, identifying factors that elevate risk of hearing loss over time—beyond level of ambient noise exposure—may uncover opportunities for intervention.

Because NIHL tends to impact hearing at the frequencies of 3, 4, and 6 kHz, unlike hearing loss due to aging, which tends to differentially affect the higher frequencies of 6 and 8 kHz, tracking the trajectory of hearing threshold level (HTL) at an average of these three frequencies (3, 4, and 6 kHz) may offer insight into NIHL susceptibility (Leensen *et al.*, 2011). Our hypothesis is that workers who experience a decline in hearing at the combined frequencies of 3, 4, and 6 kHz during the initial years of occupational noise exposure are at greater risk of further hearing decrements at these combined frequencies. If we can identify individuals at increased risk of hearing loss over time in this way, targeted, timely, and tailored interventions can be developed and deployed.

II. METHODS

This study used data available from the American Manufacturing Cohort (AMC) database, a longitudinal cohort of U.S. light and specialty metals workers (Elser *et al.*, 2019).

From this longitudinal data, we identified a study cohort comprised of workers employed by the company between 1996 and 2013, who were consistently exposed to occupational noise and enrolled in the company's hearing conservation program (HCP). Additional inclusion criteria encompassed availability of complete job histories and job-level noise sampling data throughout the study period, initial audiometric testing performed within three years of company hire date, and a minimum of eight audiograms conducted with no more than two years between consecutive audiometric tests. Demographic information for the study cohort, including age at first audiogram, sex, race/ethnicity, and history of each job held was available from the human resources data for the AMC. Race/ethnicity was categorized as White, Black, Hispanic/Latino, and Other.

The company's HCP required inclusion of all individuals who worked in areas where $\geq 5\%$ of the noise measurement samples equaled or exceeded an 8-h time-weighted average of 82 dBA (Cantley *et al.*, 2015; Tessier-Sherman *et al.*, 2017). Workers in the company's HCP underwent annual audiometric testing conducted by certified audiometric technicians in test environments designed to meet the American National Standards Institute (ANSI) standards for industrial audiometry. Available audiometric data include measurements of pure tone air conduction audiometric threshold testing results for the each test date and worker at frequencies of 0.5, 1, 2, 3, 4, and 6 kHz for each ear. Audiometric tests containing missing values for one or more frequencies in either ear were excluded. Any differences of 15 dB or more in either ear at 3, 4, or 6 kHz between an individual's consecutive tests were retained but flagged to denote a potential quality concern. From the retained audiometric records, we calculated the average audiometric threshold for the combined frequencies of 3, 4, and 6 kHz for each ear for each test date.

At the time of audiometric testing, workers completed a hearing questionnaire that included three questions regarding noise exposure outside of the study company workplace: "have you ever had any noisy habits," "did you ever hunt or shoot," and "do you presently have another noisy job?" A dichotomous variable was created for non-company workplace noise exposure during the subsequent year tests in which a positive response to any of these three questions represented non-company workplace noise exposure.

During the study period, the company's industrial hygiene standard required routine noise sampling for all jobs where exposures ever equaled or exceeded an 8-h time-weighted average of 82 dBA. Available data included multiple personal noise samples for individual jobs. We used these personal noise samples, collected over the work shift and representing $\geq 70\%$ of a shift's length, to establish an average noise exposure for each job. Utilizing a previously described process, we linked noise exposure collected by job title, to the individual workers exposed via standardized job titles (Cantley *et al.*, 2015). The noise exposure level for each job was calculated by taking the arithmetic mean of all available job-level full-shift personal noise samples between 1996 and 2013. Change in noise exposure over time was examined using trend analysis for each plant-job.

Defining early versus subsequent change in hearing threshold level represented a balance between using enough initial data to accurately define early hearing change and preserving the opportunity for intervention to mitigate hearing loss during subsequent years of occupational noise exposure. Toward this end, from the longitudinal audiometric records, we categorized results from audiometric tests conducted within 4.5 years of the initial audiogram "early tests" and later audiometric tests as "subsequent tests." Data from the "early tests" for each of these workers were used in a linear regression to calculate a hearing loss slope using the combined frequencies of 3, 4, and 6 kHz for each ear. The hearing loss slope from the worse ear, i.e., greatest hearing loss slope, was identified and used as each subject's early hearing slope (early slope). Data from the "subsequent tests" for each worker were used to calculate change in subsequent high frequency hearing for combined frequencies HTL346 in the worst ear identified in the "early tests."

The Yale University School of Medicine Human Investigations Committee granted ethical approval for this study.

A. Statistical analysis

Descriptive analysis of demographic characteristics for the cohort, baseline high frequency hearing (HTL346 worse ear), early high frequency hearing slope, noise exposure in early years and subsequent years, number of audiometric tests, and time between baseline and final audiometric test included was performed. The subsequent rate of high frequency hearing change was determined for the ear with the worse early slope using mixed (fixed and random) effects modeling with subject included as a random effect.

Occupational noise exposure, increasing age, sex, and race/ethnicity have each been associated with high frequency hearing loss; therefore, we used fixed effects linear regression to examine associations between these recognized risk factors and early slope of hearing change. To examine whether early rate of high frequency hearing (early slope) was associated with subsequent rate of change in high frequency hearing, a generalized linear mixed model was specified (Littell *et al.*, 2000). Fixed effects included age at first audiometric test, sex, race/ethnicity, early slope, mean TWA noise exposure (dBA), non-occupational noise exposure (Y/N), time from first subsequent audiometric test, and an interaction between time and early slope to test the effect that early slope has on subsequent hearing slope. The outcome was HTL346 worse ear for subsequent tests for each study cohort member. A random effect for worker and a spatial power covariance structure was specified. Recognizing the quality concerns arising from variability in audiometric testing results over time, a sensitivity analysis was performed on the study cohort subset having no flags denoting differences of 15 dB or more at 3, 4, or 6 kHz between consecutive audiometric tests. The same generalized linear mixed model described above was specified for the sensitivity analysis. All p-values were two-sided with a value of $p < 0.05$ considered statistically significant. All statistical analyses were performed using SAS version 9.4 (SAS Institute, Cary, NC).

III. RESULTS

The study cohort was comprised of 1834 workers consistently exposed to occupational noise and enrolled in the HCP who underwent periodic audiometric testing at least eight times over a time period ranging from a minimum of 8 years to a maximum of 12 years and for whom demographic information, job histories and job-level noise exposure was available. The mean number of hearing tests for the cohort was 9.9 (SD 1.0) over an average of 9.0 years (SD 0.8 years). Mean 8-h TWA noise exposure for the cohort was 81.5 dBA (SD 4.5) in the early years and 80.5 dBA (SD 4.8) in subsequent years. Flags denoting potential quality concerns between any consecutive audiograms were present for 18% of the study cohort in the "early tests" and for 25% in the "subsequent tests."

The cohort was predominately white (82.1%) and male (85.1%). Blacks represented 11.4% of the population while Hispanic/Latino comprised 4.6% of the cohort. The mean age at first hearing test for the cohort was 35.7 years (SD 7.9 years), the mean baseline HTL in the worse ear for the combined frequencies of 3, 4, and 6 kHz was 19.1 dB (SD 14.9 dB), and the mean early slope was 0.41 (SD 1.4) See Table I for a complete description of the study cohort.

Results of the fixed effects linear regression with early hearing slope as the outcome showed statistically significant associations between age at first audiometric test ($p < 0.0001$) and race/ethnicity ($p < 0.0001$), a weaker association for sex that was not statistically significant at the 0.05 level ($p = 0.096$), but no association between mean noise exposure and early high frequency hearing slope ($p = 0.534$). These results are shown in the Appendix. Results of the mixed effects model with high frequency hearing level (HTL346 worse ear) among subsequent audiometric tests as the outcome and a random effect for worker are depicted in Table II. Adjusting for the effects of age, sex, and race/ethnicity, the interaction between time and early slope showed a statistically significant association with subsequent high frequency hearing, indicating that the rate of subsequent hearing loss increased with increasing early slope in this study cohort. Additionally, as expected, males, increasing age at baseline audiometric test, and white race were all positively associated with greater subsequent hearing threshold level (Table II). Results from the sensitivity analysis yielded no meaningful differences from the full cohort analysis (data not shown).

The slope of early hearing loss (early slope) ranged from −4.9 to 13.9 for 99% of the study cohort with an interquartile range of early slope of 0.1 to 1.6. Figures 1(a), 1(b), and 1(c) show graphical depictions of the mixed model results, for 30 year-old white, black, and Hispanic/Latino male workers, respectively, projected over 16 years of follow-up with different early high frequency hearing slopes (early slopes equal to −2, 0, 2, 4, or 6) to better illustrate observed associations. As depicted, workers with a steeper rate of change in high frequency hearing during the early years, i.e., early slope = 6 versus early slope = 0, are at higher risk of more rapid subsequent high frequency hearing loss and this effect was more pronounced for white workers compared to black or Hispanic/Latino workers.

IV. DISCUSSION

To our knowledge, this work is the first attempt to describe relationships between early hearing change and subsequent hearing loss trajectories for career-long occupationally noise-exposed workers. Our study results provide evidence that the rate at which high frequency hearing loss occurs during the early years of workplace noise exposure predicts subsequent high frequency hearing loss trajectories among occupationally noise exposed workers. As anticipated, older age, male sex,

TABLE I. Descriptive statistics for the study cohort of occupationally noise-exposed manufacturing workers. N = number of persons in the study cohort; SD = standard deviation; IQR = inter-quartile range; kHz = kilohertz; dB = decibels; dBA = A-weighted decibels; TWA = time-weighted average.

	N	%	Mean	SD	IQR
Total cohort	1834	100			
Sex Male	1561	85.1			
Age at first test (years)			35.7	7.9	29.5, 41.2
Age group at first test: <25 years old	128	6.8			
25 to 34 years old	838	44.2			
35 to 44 years old	659	34.8			
45 to 54 years old	260	13.7			
≥55 years old	11	0.6			
Hearing threshold level (average 3, 4, 6 kHz) (dB) worse ear−initial audiogram			11.0	8.2	6.2, 13.8
Race White	1506	82.1			
Black	210	11.4			
Hispanic/Latino	85	4.6			
Other	33	1.8			
Years between first and last audiogram used			9.0	0.79	8.8, 9.6
Noise exposure dBA early years (mean 8-h TWA)			81.5	4.5	79.3, 84.6
Noise exposure dBA subsequent years (mean 8-h TWA)			80.5	4.8	78.3, 83.8
Any non-company workplace noise exposure Yes	1087	59.3			
No	693	37.8			
Missing	54	2.9			
Specific non-company workplace noise exposure					
Ever have any noisy habits = yes?	707	38.5			
Ever hunt or shoot = yes?	794	73.0			
Ever hold another noisy job = yes?	395	21.5			
Number hearing tests			9.9	1.0	9, 11
Early hearing slope at 346 kHz worse ear (Audiometric testing within the first 4 years)			0.9	1.3	0.1, 1.6
Subsequent hearing slope at 346 kHz worse ear			0.6	1.5	−0.2, 1.2
Hearing threshold level (average 3, 4, 6 kHz) (dB) worse ear—last included audiogram			20.4	16.3	8.3, 26.7

and white race were each associated with higher rates of hearing loss. After adjusting for these recognized risk factors as well as self-reported non-occupational noise exposure, those who displayed higher rates of early hearing loss continued to display greater rates of subsequent hearing loss compared those with slower rates of early hearing loss. This finding reveals a potentially impactful opportunity to direct enhanced hearing loss prevention interventions to the subset of workers at greatest risk of future hearing loss.

Interestingly, and providing support to the somewhat counter-intuitive evidence previously reported by Rabinowitz *et al.* (2007) that workers with higher levels of ambient noise exposure experienced less hearing loss than those with lower ambient noise exposure levels, mean workplace noise

TABLE II. Mixed model results showing association between early hearing slope and subsequent change in hearing (outcome: average 346 kHz worse ear) with a random effect for person. CI = confidence interval.

Fixed effects	Estimate	Standard Error	Lower CI	Upper CI	Pr > |t|	F value	p-value
Intercept	−11.097	5.790	−22.453	0.259	0.055		
Age initial hearing test	0.778	0.040	0.699	0.957	<0.0001	374.84	<0.0001
Sex: Male	reference	—	—	—	—	69.48	<0.0001
Female	−7.694	0.923	−9.504	−5.885	<0.0001		
Race: White	reference	—	—	—	—	11.83	<0.0001
Black	−5.369	0.987	−7.303	−3.435	<0.0001		
Hispanic/Latino	−3.194	1.488	−6.111	−0.276	0.032		
Other	3.218	2.289	−1.270	7.706	0.160		
Non-company noise exposure No	reference	—	—	—	—	17.92	<0.0001
Yes	2.788	0.658	1.497	4.078	<0.0001		
Occupational noise exposure (mean 8-h TWA)	−0.018	0.068	−0.150	0.115	0.792	0.07	0.792
Early hearing slope (average 346 kHz worse ear) worse ear from audiogram in initial four years	2.837	0.246	2.354	3.320	<0.0001	132.81	<0.0001
Time of subsequent hearing test (years)	0.416	0.030	0.356	0.475	<0.0001	189.13	<0.0001
Early hearing slope * time of subsequent hearing test	0.103	0.018	0.067	0.139	<0.0001	31.32	<0.0001
Random effect for person							
Variance person	165.89	5.665					
Residual	12.548	0.211					

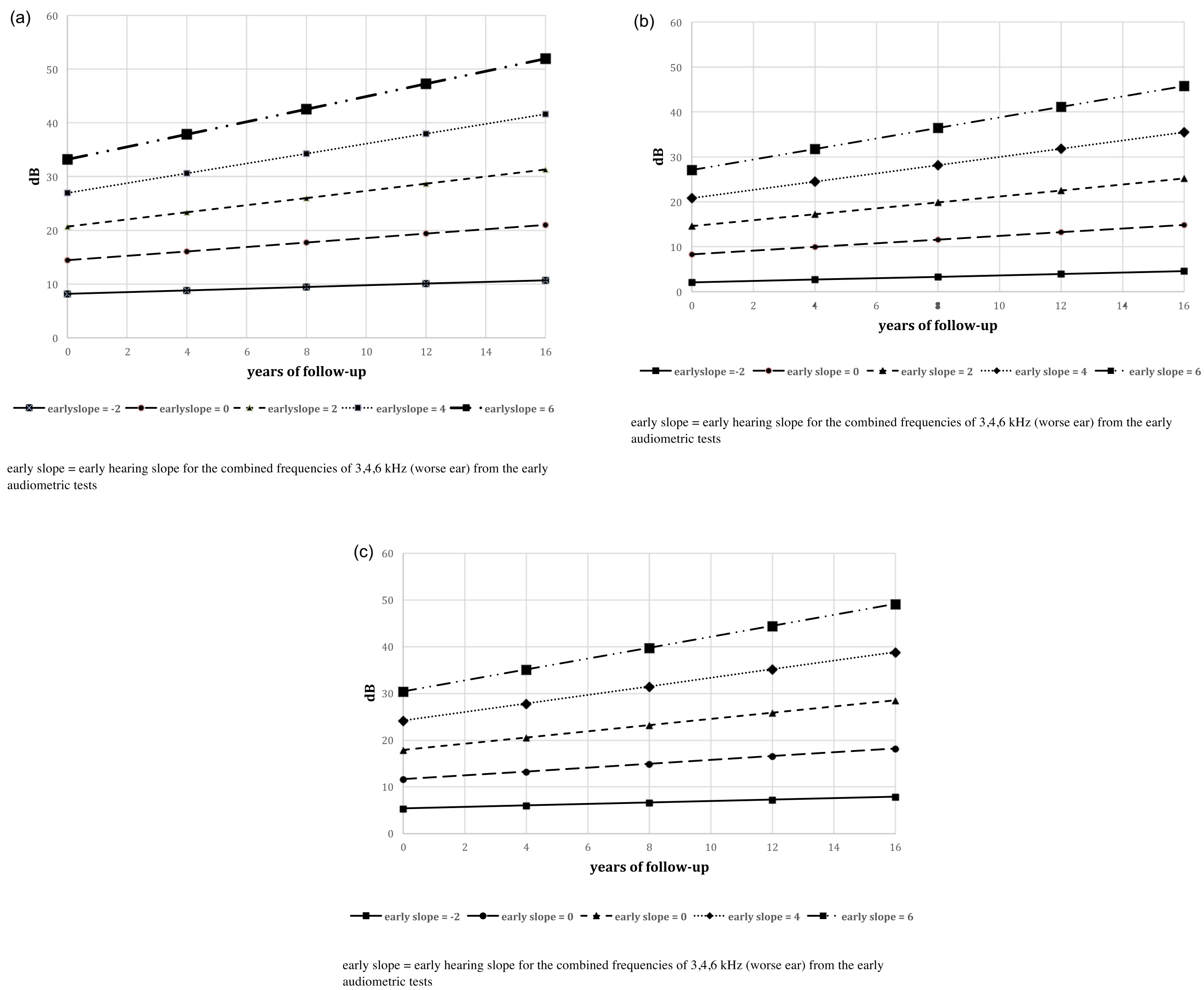

FIG. 1. (Color online) (a) Predicted hearing level (dB) over time for 30 year-old white males with different early hearing loss slopes. (b) Predicted hearing level (dB) over time for 30 year-old black males with different early hearing loss slopes. (c) Predicted hearing level (dB) over time for 30 year-old Hispanic/Latino males with different early hearing loss slopes.

exposure showed no association with early or subsequent rate of hearing loss among this study cohort. In contrast, worker self-report of other source of noise exposure, including noisy hobbies or holding a second noisy job, was associated with higher rate of hearing loss in this cohort.

Company policy required that all workers in the HCP wear hearing protection when working in noise. Unavailable however, was any information regarding fit testing of hearing protection devices (HPDs) or consistency of HPD use, which certainly may have impacted our finding that noise exposure was not associated with early or subsequent rate of subsequent hearing change. Another possible explanation for this negative finding is that average noise exposure in the cohort was fairly low (81.5 dBA) and may be below the threshold necessary to observe meaningful associations. A third possible explanation is that available measures of noise exposure for this cohort—8-h TWAs—are inadequate to discern associations.

Our finding that workers with steeper early slopes of hearing change were more likely to experience steeper subsequent hearing loss slopes is interesting and could indicate that this subset of workers at risk for more rapid hearing loss may, in fact, represent workers who inconsistently or ineffectively wear HPDs or wear poorly fitting HPDs that fail to offer adequate protection. This is worthy of exploration in future studies. Because evidence suggests that interventions aiming to change behaviors are more effective than non-tailored approaches (Morata and Meinke, 2016), targeted interventions tailored specifically to workers with accelerated rates of early hearing loss are recommended.

Focus on the prevention of NIHL among US workers exposed to noisy occupational environments has improved since OSHA mandated hearing protection programs (Suter, 2009); however much work remains to be done. Previous research has shown that susceptibility to noise exposure varies greatly among individuals with similar levels of noise exposure (Sliwinska-Kowalska *et al.*, 2006) with some workers experiencing accelerated hearing loss over the course of their employment compared to others. Consequently, it is possible that our study results have identified a group of workers who are biologically more vulnerable to hearing loss from noise exposure. Regardless, the ability to predict those at risk for accelerated hearing loss would enable timely and targeted interventions tailored specifically to these at risk workers who could benefit from interventions designed to ensure proper fit and consistent usage of appropriate HPDs during noise exposure both at work and during recreational activities.

Our study has many strengths, including a large, longitudinal noise-exposed cohort for whom repeated audiometric records were available and allowed for calculation of individual-level changes in hearing over time. Availability of job-level noise sampling data and self-report of non-company noise exposure enabled us to adjust for these variables in statistical models and enhance confidence in our findings. And, access to demographic data including age, sex, and race/ethnicity allowed additional model adjustment for these known predictors of hearing loss. Despite these strengths, notable limitations remain. Information on hearing level prior to commencing employment at the study company was unavailable. Because the mean age at our study baseline (initial audiogram date) was nearly 36 years, unobserved changes in early hearing could have impacted these results. We also lacked any information on the specifics of HPD usage, including fit testing. These limitations notwithstanding, our study results hold promise that an opportunity to identify workers at risk for accelerated hearing loss and target hearing loss prevention strategies during a time sensitive window may result in preservation of hearing by slowing the predicted rate of hearing loss.

V. CONCLUSION

The results of this study support our stated hypothesis that early slope of hearing predicts subsequent hearing slope. Among this study cohort, after adjusting for many recognized risk factors for NIHL, noise exposed workers with accelerated rates of early hearing loss were at greater risk of accelerated hearing loss subsequently. These results have important implications for understanding not only the expected hearing loss of noise-exposed workers during working life but also quality of life in retirement, and suggest that by using results from audiometric testing in the early years of occupational noise exposure, a group of workers at risk for accelerated future hearing loss can be identified and targeted for interventions to mitigate future loss.

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APPENDIX: PREDICTORS OF EARLY HEARING SLOPE (HTL346 WORSE EAR)

We used fixed effects linear regression to examine associations between early slope of hearing change (HTL346 worse ear) and recognized risk factors, namely, increasing age, sex, race/ethnicity, and occupational noise exposure. The linear regression results are depicted in Table III.

TABLE III. Predictors of early hearing slope (HTL346 worse ear): results from linear regression.

	Estimate	Standard Error	Pr > |t|	F value	Pr > F
Age initial hearing test	0.022	0.004	<0.0001	26.54	<0.0001
Sex: Female	−0.220	0.093	0.096	−1.67	0.096
Male	reference	—	—		
Race: Black	−0.414	0.096	<0.0001	7.76	<0.0001
Hispanic/Latino	−0.116	0.144	0.715		
Other	−0.500	0.226	0.028		
White	reference	—	—		
Noise exposure (mean 8 h TWA)	−0.006	0.007	0.534	0.39	0.534

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