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ORIGINAL ARTICLE



Population-based age adjustment tables for use in occupational hearing conservation programs

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ABSTRACT

Objective: In occupational hearing conservation programmes, age adjustments may be used to subtract expected age effects. Adjustments used in the U.S. came from a small dataset and overlooked important demographic factors, ages, and stimulus frequencies. The present study derived a set of population-based age adjustment tables and validated them using a database of exposed workers.

Design: Cross-sectional population-based study and retrospective longitudinal cohort study for validation.

Study sample: Data from the U.S. National Health and Nutrition Examination Survey (unweighted $n = 9937$) were used to produce these tables. Male firefighters and emergency medical service workers (76,195 audiograms) were used for validation.

Results: Cross-sectional trends implied less change with age than assumed in current U.S. regulations. Different trends were observed among people identifying with non-Hispanic Black race/ethnicity. Four age adjustment tables (age range: 18–85) were developed (women or men; non-Hispanic Black or other race/ethnicity). Validation outcomes showed that the population-based tables matched median longitudinal changes in hearing sensitivity well.

Conclusions: These population-based tables provide a suitable replacement for those implemented in current U.S. regulations. These tables address a broader range of worker ages, account for differences in hearing sensitivity across race/ethnicity categories, and have been validated for men using longitudinal data.

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Introduction


Serial audiometric monitoring is used to identify changes in hearing thresholds and for reporting adverse worker health outcomes. Adjustments for the expected effects of age on longitudinal differences are permitted in some regulations (U.S. Federal Railroad Administration [FRA] 2006; U.S. Mine Safety and Health Administration [MSHA] 1999; U.S. Occupational Safety and Health Administration [OSHA] 1983), but are not required and are not recommended by the U.S. National Institute for Occupational Safety and Health (NIOSH) (1998). The U.S. Department of Defense (2018) does not permit age adjustments when assessing changes in audiometric thresholds. These age adjustments, which are often called “age corrections”, are intended

to “... allow for the contribution of aging to the change in hearing level by adjusting the most recent audiogram” (OSHA 1983, p. 9781). The adjustments applied to the audiogram are intended to represent the unavoidable changes in hearing sensitivity due to the inexorable effects of aging, such as the loss of hearing sensitivity associated with senescence at the cellular level.

In the context of occupational hearing conservation, the issue of allocating an observed change in hearing into an age component and a non-age component carries with it debates regarding fairness. Paraphrasing from Dobie (2015), age adjustments that transform a significant change in hearing to a non-significant change can over-allocate the change to age effects, which is unfair to the worker. Conversely, neglecting the component of the observed hearing loss known to be due to age is unfair to the employer or other responsible party. At the group level, incorrect allocation would alter the entire distribution of audiometric changes, thus distorting estimates of occupational exposures on hearing.

It has been argued that reasonable approaches to allocating between age and non-age components of an observed hearing

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change can be applied by subtracting estimates of age effects from the observed change (Dobie 2015). However, any such approach depends on the validity of the age adjustments that are applied, and there can be no reasonable defence for applying age adjustments that are known to be incorrect.

It is impossible to know the hearing sensitivity that an individual worker would have had in an alternate history that did not include occupational exposures. Additionally, it is inappropriate to apply median population distribution values to that exposed worker to estimate the hearing change not caused by occupational exposures. Cross-sectional trends are influenced by the combined effects of events (e.g. acute disorders, trauma, infection) and conditions that might be rare on the individual level (e.g. hereditary/genetic disorders) but have a collective impact on the distribution of hearing thresholds at the population level. These effects would be increasingly potent as a function of increased time at risk (i.e. correlated with age, but not an inexorable effect of age). The effects would be minimal on the tail of the distribution with better hearing sensitivity and would increase as consideration moves to the opposite tail of the distribution. There is no necessary correspondence between a specified percentile of a distribution of cross-sectional trends and that same percentile of a distribution of longitudinal changes. Despite these deficiencies, current regulations permit the use of age adjustment, so it is important that the age adjustments represent current expected longitudinal changes as accurately as possible, even if they must be derived from cross-sectional data.

The study of the inexorable effects of aging on the human auditory system is open to many methodological challenges. It is difficult to separate the effects solely due to aging from the cumulative effects of noise exposures associated with normal life in a society (i.e. socioacusis) and the cumulative effects of otologic diseases, ototoxic exposures, and injuries not involving noise exposure (i.e. nosoacusis) (Glorig and Nixon 1962; Kryter 1985; Ward 1977). In human populations, longitudinal experimental control of such factors is impossible, and central tendencies derived from trends across cross-sectional samples can mistakenly allocate to age the cumulative effects of socioacusis and nosoacusis.

The problem of separating socioacusis and nosoacusis from inexorable changes in hearing associated with age may be intractable. However, outcroppings of socioacusis and nosoacusis are observable as changes in cross-sectional trends over time. For example, improvements in the hearing sensitivity of the U.S. population have been observed across all age groups during the last 60 years (Hoffman et al. 2010, 2012, 2017, 2019), with significant improvements over the brief period between 1999–2004 and 2011–2012 (Hoffman et al. 2017). Such improvements are attributable to changes in socioacoustic and nosoacoustic exposure profiles rather than changes in the inexorable effects of aging.

The NIOSH age adjustment tables used in most current U.S. regulations were developed using relatively small numbers of people (380 men and 206 women, divided equally into five age groups including 76 men and 41 women) (Lempert and Henderson 1973) and were never validated using longitudinal data. Across groups of men in the Lempert and Henderson study, mean ages ranged between 23 and 55 years. Mean ages for groups of women were not reported. The NIOSH age adjustment tables were derived through a curvilinear ordinary least-squares regression fitting of cross-sectional trends in median thresholds as a function of mean age across the five groups. The fitted regression function was then extrapolated to cover the age range from 20 to 60 years. The data were screened to exclude participants with two or more years in a noisy job, exposure to military

weapon noise for 100 days or more, one or more years of military combat experience, or routine military non-weapon noise (e.g. aircraft engines) exposure to civilian firearm noise (1000 rounds in a year or 500 rounds per year for five years), history of head trauma or otologic disease, excessive cerumen, and indicators of inaccurate tests (e.g. audiometric irregularities, reports of significant exposure in the 14 hours prior to the exam). Noise-exposed participants were not necessarily excluded if they wore hearing protection. When considered from a contemporary perspective, these exclusion criteria would not be expected to yield a sample free from the effects of noise on hearing sensitivity.

Changes in the typical hearing sensitivity of the U.S. population in the last half-century and the contemporary availability of more comprehensive datasets and modern analytic techniques present an opportunity to consider whether the age adjustment tables developed by NIOSH nearly fifty years ago should be revisited. In addition, there are other reasons to consider updating these tables. For example, age-related reductions in hearing sensitivity tend to accelerate with age, and for users of age adjustment, OSHA requires the use of the age adjustment value at age 60 for all workers aged 60 and over (i.e. workers over the age of 60 are treated as if they were 60 years old). Disparate sources also indicate that there are a large number of older noise-exposed workers. One large provider of occupational audiometric testing services found that a significant proportion of workers (8% of 233,200 exams) were older than age 60 (Dr. Timothy Rink, HTI Incorporated, personal communication, 21 February 2019). Around 1.3 million workers (approximately 5%) in a limited set of occupations likely to involve noise exposure (installation, maintenance, repair, production, transportation, and material moving) were aged 65 and older (U.S. Bureau of Labor Statistics 2019). Also, of the nearly 2.2 million noise-exposed workers included in the NIOSH Occupational Hearing Loss Surveillance Project Dataset from 2006 to 2019, 6.3% (137,432 workers) were aged 61 or older (Dr. Elizabeth Masterson, NIOSH, personal communication, October 11, 2019). The lack of an extended age adjustment table beyond age 60 could lead to an underestimate of age effects, which might result in an over-allocation of observed hearing changes to occupational exposures.

Furthermore, cross-sectional trends in hearing sensitivity differ with race/ethnicity (Driscoll and Royster 1984; Flamme, Deiters, and Needham 2011; Royster et al. 1980). Lempert and Henderson (1973) did not report the race/ethnicity of the screened sample used to derive the NIOSH age adjustment tables, and there were too few participants in that study to produce stable estimates for race/ethnicity subgroups. Finally, the identification of the median cross-sectional trend by Lempert and Henderson (1973) is understandable given the small sample size, but the median could over-represent the effects of socioacusis and nosoacusis, and the use of a lower percentile of the distribution would reduce these effects.

The absence of the 8 kHz stimulus frequency from the NIOSH age adjustment tables is consistent with concerns at the time regarding the reliability of hearing threshold measurements at that frequency, which led to a dearth of data on which to base age adjustments. However, measurements at the 8 kHz stimulus frequency are common in both clinical and research practice, and are now known to have sufficient reliability to justify inclusion in routine audiometric monitoring (Flamme et al. 2014). In the occupational hearing conservation context, thresholds at 8 kHz are particularly important for discriminating between the audiometric configurations commonly associated with aging (i.e.

a monotonic reduction in hearing sensitivity with frequency) and noise exposure (i.e. a notched configuration with poorest hearing sensitivity at 3, 4, or 6 kHz). The absence of adjustments for the 8 kHz stimulus frequency stymies the discrimination of aging effects from the effects of noise.

During the development of the FRA's noise exposure regulation in the mid-2000s, NIOSH recommended that age adjustment should not be applied to individual audiograms. NIOSH also noted that the NIOSH age tables implemented by OSHA did not account for racial differences in age-related hearing loss trajectories or for the acceleration in age-related hearing loss among persons older than age 60, and that the source data for the NIOSH age tables (i.e. Lempert and Henderson 1973) might not represent contemporary cross-sectional trends. NIOSH further advised that, if age adjustments were to be included in the FRA regulation, those adjustments should be derived from population-based studies like the U.S. National Health and Nutrition Examination Survey (NHANES), use tables that represent differences across race/ethnicity categories, and base age adjustments on cross-sectional trends at least one standard deviation below the mean (FRA 2006, p. 63098). Age adjustment tables meeting these criteria were not available at that time, and the necessary data, analyses, and expertise were also not available to the FRA (FRA 2006, p. 63099). The FRA subsequently adopted the use of the NIOSH age tables (i.e. the tables arising from Lempert and Henderson 1973) in their regulation.

Attempts to extend age adjustment tables beyond age 60 (Dobie and Wojcik 2015), have been complicated by coarse representations of age, lack of screening based on otologic and noise exposure history, inability to account for differences in hearing across race/ethnicity categories (Driscoll and Royster 1984; Flamme, Deiters, and Needham 2011; Royster et al. 1980) and the preservation of the NIOSH age adjustment tables for some age segments. Further, the Dobie and Wojcik (2015) age adjustment proposals were based on NHANES cycles between 1999 and 2006, and the hearing sensitivity data in the 1999–2004 NHANES cycles have been shown to no longer represent the U.S. population (Hoffman et al. 2017).

The present study was conducted to compare the 1970s-era NIOSH age adjustment tables against recent cross-sectional trends observed in audiometric data sampled and analysed to produce results that represent the non-institutionalised U.S. population. The recent cross-sectional trends observed in the U.S. population were then compared against longitudinal changes observed in a large group of noise-exposed workers. This work resulted in population-based age adjustment tables for the frequency range of 0.5 through 8 kHz that represent contemporary longitudinal changes more accurately than the original NIOSH age adjustment tables included in current U.S. regulations.

Methods

Cross-sectional trends

Data for identifying cross-sectional trends were drawn from the National Health and Nutrition Examination Survey (NHANES) cycles between 2005 and 2012. The NHANES data are representative of the non-institutionalised, non-military U.S. population, and are deidentified and publicly-available via the U.S. National Center for Health Statistics (NCHS) (<https://www.cdc.gov/nchs/nhanes/index.htm>, last accessed on 28 May 2019). The NHANES

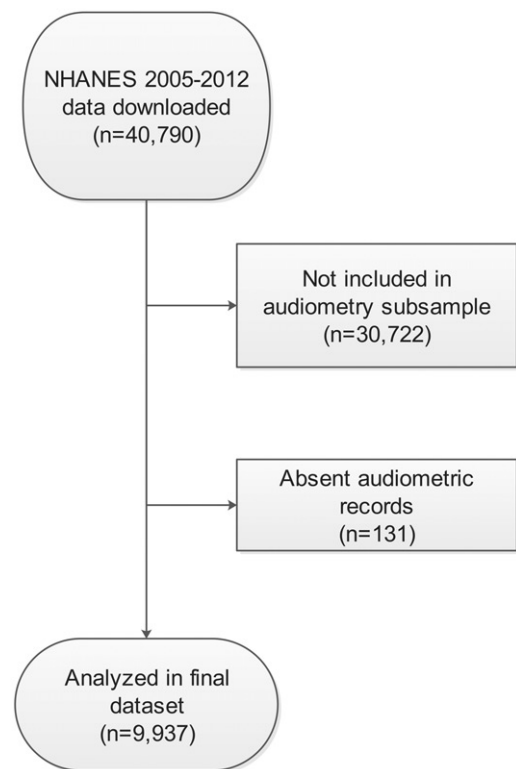


Figure 1. Participant flow diagram for cross-sectional study.

data are the product of a nationally-representative complex sampling procedure that is repeated in two-year cycles.

Audiometric data were obtained on a subsample of NHANES participants. A total of 9937 participants (5096 men and 4841 women over the age of 12 years) were included in the complete dataset (Figure 1). The oldest participants were older than 85 years, and the exact ages of participants over age 85 were not released to preserve participant confidentiality. Participant demographics are represented in Table 1.

Instrumentation, stimuli, and procedure

Audiometric thresholds were assessed using microprocessor-driven audiometers (Interacoustics AD226) with TDH-39P or TDH-49P supra-aural earphones. Insert earphones (Etymotic ER-3A) were used in cases of excessive threshold asymmetry or suspected ear canal collapse under the supra-aural earphones. The status of the middle ear was assessed via tympanometry (Micro Audiometrics Earscan). Testing was conducted in sound-attenuating booths with ambient noise levels sufficient for testing to 0 dB HL. Further details regarding test instrumentation can be found on the NCHS NHANES website (<https://www.cdc.gov/nchs/nhanes/index.htm>).

Pure tones at stimulus frequencies of 0.5, 1, 2, 3, 4, 6, and 8 kHz were used for assessing thresholds in each ear, with a re-test at 1 kHz for assessing response consistency. Within each stimulus frequency, thresholds were obtained using a modified Hughson-Westlake procedure (Carhart and Jerger 1959) programmed within the microprocessor-driven audiometer. Trained technicians conducted manual testing as necessary (e.g. poor response reliability, long response lag). Technicians were trained by an audiologist from the National Institute for Occupational Safety and Health (author CLT), who also continuously

Table 1. Cross-sectional data demographics by gender.

	Men			Women			Total		
	NHANES sample n	U.S. Population N*	Weighted %	NHANES sample n	U.S. Population N*	Weighted %	NHANES sample n	U.S. Population N*	Weighted %
Age									
12–19	2273	15,988,338	7.0	2131	15,269,272	6.7	4404	31,257,610	13.7
20–29	448	19,203,877	8.4	394	18,347,991	8.0	842	37,551,868	16.4
30–39	407	17,065,846	7.5	357	15,979,406	7.0	764	33,045,252	14.4
40–49	368	18,894,568	8.3	376	18,777,814	8.2	744	37,672,382	16.5
50–59	375	18,868,246	8.2	406	19,679,618	8.6	781	38,547,864	16.8
60–69	375	13,287,142	5.8	355	14,390,715	6.3	730	27,677,857	12.1
70–79	531	6,703,113	2.9	501	8,392,637	3.7	1032	15,095,750	6.6
80+	319	3,081,808	1.3	321	4,996,898	2.2	640	8,078,706	3.5
Race/ethnicity									
Mexican American (MA)	935	10,008,618	4.4	885	8,499,477	3.7	1820	18,508,095	8.1
Hispanic, other (HI)	391	6,580,880	2.9	396	6,443,719	2.8	787	13,024,599	5.7
Non-Hispanic White (NHW)	1991	76,079,387	33.2	1833	78,463,635	34.3	3824	154,543,023	67.5
Non-Hispanic Black (NHB)	1288	12,308,441	5.4	1276	14,445,305	6.3	2564	26,753,746	11.7
Unlisted categories**	491	8,115,612	3.5	451	7,982,215	3.5	942	16,097,826	7.0
Occupational noise exposure									
No	3471	62,819,385	27.4	4244	93,951,474	41.0	7715	156,770,859	68.5
Yes	1625	50,273,553	22.0	597	21,882,877	9.6	2222	72,156,430	31.5
NHANES cycle									
2005–2006	1391	10,044,354	4.4	1353	11,499,497	5.0	2744	21,543,851	9.4
2007–2008	603	5,420,344	2.4	538	5,105,765	2.2	1141	10,526,109	4.6
2009–2010	1129	10,308,561	4.5	1062	12,053,545	5.3	2191	22,362,106	9.8
2011–2012	1973	87,319,679	38.1	1888	87,175,544	38.1	3861	174,495,223	76.2
Total	5096	113,092,938	49.4	4841	115,834,351	50.6	9937	228,927,289	100.0

*Estimated using NHANES sample weights; **includes all other race/ethnicity categories (including mixed race), refused, and not ascertained.

monitored the performance of each technician and reviewed data prior to public release.

Analyses

Data from each NHANES cycle (2005–2012) were combined into a single dataset, with adjustments to complex sample weights appropriate for the number of combined NHANES cycles. Complex sample analyses of univariable demographics were conducted during preliminary examinations of the data. Cross-sectional changes in hearing sensitivity as a function of age were identified using quantile regression analyses of each participant's best threshold at each stimulus frequency. In accordance with the NIOSH advice to the FRA (FRA 2006, p. 63098), curves were fitted to a lower percentile than the median. The 25th percentile (i.e. the value at which 25% of the observations indicated better hearing and 75% of observations indicated worse hearing) was used. These analyses utilised adjusted NHANES sample weights and balanced repeated replicate (BRR) methods were used for variance estimation (Korn and Graubard 1999). Briefly, the BRR method involves extracting a structured series of half-samples of a complex dataset. Interested readers are referred to Korn and Graubard (1999), Heeringa, West, and Berglund (2010), and the Stata Survey Data Reference Manual (<https://www.stata.com/manuals/svy.pdf>, last accessed 28 May 2019) for details.

Data from participants aged 12 to 85+ years were used to define cross-sectional trends, and only the results for people aged 18 and over are represented in this report. Separate quantile regression models were developed for women and men.

Initial analyses were conducted using model-building principles described by Hosmer, Lemeshow, and Sturdivant (2013). Briefly, these principles involved assessing univariable relationships, including all near-significant univariable relationships (e.g. $p < 0.20$) in an initial (main effects) multivariable model, discarding variables failing to retain significance ($p < 0.05$) in the

multivariable model, and finally testing interactions among the remaining factors. Fourteen separate quantile regression models were developed at each combination of stimulus frequency and gender.

Final regression models contained only terms for factors that could be ascertained by personnel reviewing occupational hearing conservation database records, including age, gender, and race/ethnicity. Self-reported occupational noise exposure was controlled by including this factor in all models. Age adjustment tables were based on trends observed among those not reporting exposure to occupational noise.

In order to ensure consistency in model structures across stimulus frequencies and gender, terms that were significant in any of the fourteen models were retained as predictors in all regression models. The significance status of each coefficient is represented in Table 2. Sensitivity analyses were conducted to ensure that the significant factors excluded from the final analyses did not influence the relationships between hearing sensitivity, age, gender, and race/ethnicity.

Longitudinal validation

Data for comparing cross-sectional trends against observations of longitudinal change among exposed workers were drawn from hearing exam records at the New York City Fire Department (FDNY). These analyses were incidental to an evaluation of auditory consequences of exposure to the 11 September 2001 attacks on the World Trade Center. Participants were 9340 FDNY male firefighters and emergency medical service (EMS) workers (5% identified as having non-Hispanic Black race/ethnicity) who had serial hearing exams within the FDNY occupational health clinic. Initial hearing exams were obtained at the start of employment and repeated approximately annually throughout the worker's tenure as a firefighter or EMS worker within FDNY. Workers with hearing exams between the years of 1999 and 2011 were included in these analyses.

Table 2. Coefficient values in multilevel model final cross-sectional analysis.

Frequency	Constant	Age	Age ²	Age ³	NHB	NHB*age	OccNoise	OccNoise*age
Women								
0.5	0.267	0.0522	-4.35×10^{-3}	7.61×10^{-5}	-0.675	0.0251	-0.771	2.96×10^{-2}
1	-0.892	0.128	-5.80×10^{-3}	8.20×10^{-5}	-4.53×10^{-2}	2.49×10^{-3}	-1.117	4.81×10^{-2}
2	-3.51	0.403	-1.48×10^{-2}	1.67×10^{-4}	-0.956	0.0399	-1.813	6.21×10^{-2}
3	-11.1	0.613	-1.51×10^{-2}	1.64×10^{-4}	5.08	-0.107	-0.329	4.59×10^{-2}
4	-13.3	0.833	-2.02×10^{-2}	2.07×10^{-4}	3.22	-0.069	-0.773	7.22×10^{-2}
6	-4.91	0.697	-1.81×10^{-2}	2.08×10^{-4}	-1.37	-3.60×10^{-2}	-1.88	7.59×10^{-2}
8	-16.3	1.49	-3.80×10^{-2}	3.80×10^{-4}	1.29	-4.60×10^{-2}	-0.877	6.30×10^{-2}
Men								
0.5	11.0	-0.599	8.38×10^{-3}	-8.10×10^{-6}	-4.34	6.21×10^{-2}	2.11	4.42×10^{-4}
1	0.624	-0.0594	7.35×10^{-4}	2.30×10^{-5}	-1.21×10^{-2}	-3.76×10^{-3}	-0.633	3.07×10^{-2}
2	-2.18	0.293	-1.23×10^{-2}	1.54×10^{-4}	-0.168	9.35×10^{-3}	-2.17	6.44×10^{-2}
3	1.06	-0.0983	-8.50×10^{-5}	8.43×10^{-5}	1.55	-7.23×10^{-2}	-1.55	7.23×10^{-2}
4	-5.70	0.297	-7.31×10^{-3}	1.44×10^{-4}	5.39	-0.199	-3.15	0.164
6	-7.31	0.842	-2.27×10^{-2}	2.78×10^{-4}	0.353	-9.98×10^{-2}	-1.50	0.105
8	-10.2	0.945	-2.40×10^{-2}	3.01×10^{-4}	2.63	-0.147	-0.684	6.86×10^{-2}

All factors (i.e. age, NHB race/ethnicity, and occupational noise) produced a significant improvement in overall model fit. Significant individual coefficients ($p < 0.05$) are printed in bold.

A total of 76,185 exam records were included in the comparison of observed longitudinal changes against cross-sectional trends. Analyses of these records was performed by one of the authors (DG) at FDNY. The analyses of FDNY data were conducted under a research protocol reviewed and approved by the Institutional Review Board of the Albert Einstein College of Medicine.

Instrumentation, stimuli, and procedure

Audiometric thresholds were obtained using microprocessor-driven audiometers (e.g. Tremetrics RA500 audiometer) with TDH-39P supra-aural earphones. Tests were conducted in sound-attenuating booths having less ambient noise than OSHA ambient noise limits. Pure tone hearing thresholds were obtained in each ear using a modified Hughson-Westlake technique (Carhart and Jerger 1959) at stimulus frequencies of 0.5, 1, 2, 3, 4, 6, and 8 kHz.

Analyses

Following the initial (i.e. baseline) exam, age-adjusted threshold changes were derived by subtracting 25th percentile cross-sectional trends from observed changes from baseline thresholds at each stimulus frequency.

Results

Cross-sectional trends

The form of the relationship between age and pure tone threshold was evaluated by transforming age as a polynomial through the fifth order (i.e. by including age, age², age³, age⁴, and age⁵ as predictors) in preliminary analyses of cross-sectional trends at two frequencies, one expected to be minimally affected by noise and aging (1 kHz) and the other expected to be affected maximally by noise and aging (6 kHz). The relationship between age and hearing thresholds was best described by a cubic (i.e. third order) polynomial, which was used in all subsequent analyses. The form of the regression equation was

$$\begin{aligned} \text{HL} = & \text{Constant} + b_1\text{Age} + b_2\text{Age}^2 + b_3\text{Age}^3 + b_4\text{NHB} \\ & + b_5(\text{NHB} * \text{Age}) + b_6\text{OccNoise} + b_7(\text{OccNoise} * \text{Age}) \end{aligned} \quad (1)$$

where HL represents the predicted threshold for a given combination of gender and stimulus frequency, Constant represents the y-intercept for the fitted equation, Age represents the participant's age in years, NHB is a binary indicator of Non-Hispanic Black race/ethnicity (a multiplier of 1 is to be used for people identifying with non-Hispanic Black race/ethnicity and a multiplier of 0 for all other races/ethnicities), OccNoise is a binary indicator of occupational noise exposure (evaluated with a multiplier of 0 to return estimates for workers with no reported occupational exposure), and b represents the regression coefficient associated with each variable.

The coefficients included in Table 2 were used to produce the tabled values in Supplementary Appendices A and B, with the exception of 0.5 kHz for men, as described below. For example, the tabled value at 4 kHz for women aged 31 and identifying as non-Hispanic Black was 0 dB HL,

$$\begin{aligned} 0 \text{ dB HL} = & -13.26973 + (0.83321*31) + (-0.02022*31^2) \\ & + (0.00021*31^3) + (3.21559*1) + (-0.06859*1*31) \\ & + (-0.77283*0) + (0.07216*31*0) \end{aligned} \quad (2)$$

and the tabled value at 6 kHz for women aged 65 and identifying as a race/ethnicity other than non-Hispanic Black was 21 dB HL,

$$\begin{aligned} 21 \text{ dB HL} = & -4.90872 + (0.69727*65) + (-0.01810*65^2) \\ & + (0.00021*65^3) + (-1.37287*0) \\ & + (-0.03606*0*65) + (-1.87539*0) \\ & + (0.07593*65*0) \end{aligned} \quad (3)$$

Quantile regression curves fitted to the 25th percentile cross-sectional trend returned values within one audiometric step of 0 dB HL (i.e. -4 to 3 dB HL, see Supplementary Appendices A and B) at age 18, and this result is consistent with the expected hearing sensitivity of a young, otologically normal population. The curves differed as a function of age, gender, self-reported race/ethnicity, and self-reported occupational noise exposure (Figures 2 and 3; Supplementary Appendices A and B), and both the locations and slopes of the curves differed from the NIOSH age tables. The NIOSH tables overestimate the age-related changes observed in contemporary cross-sectional trends.

Thresholds increased (i.e. worsened) monotonically with age, with the exception of a slight reduction (e.g. 3 dB) in expected

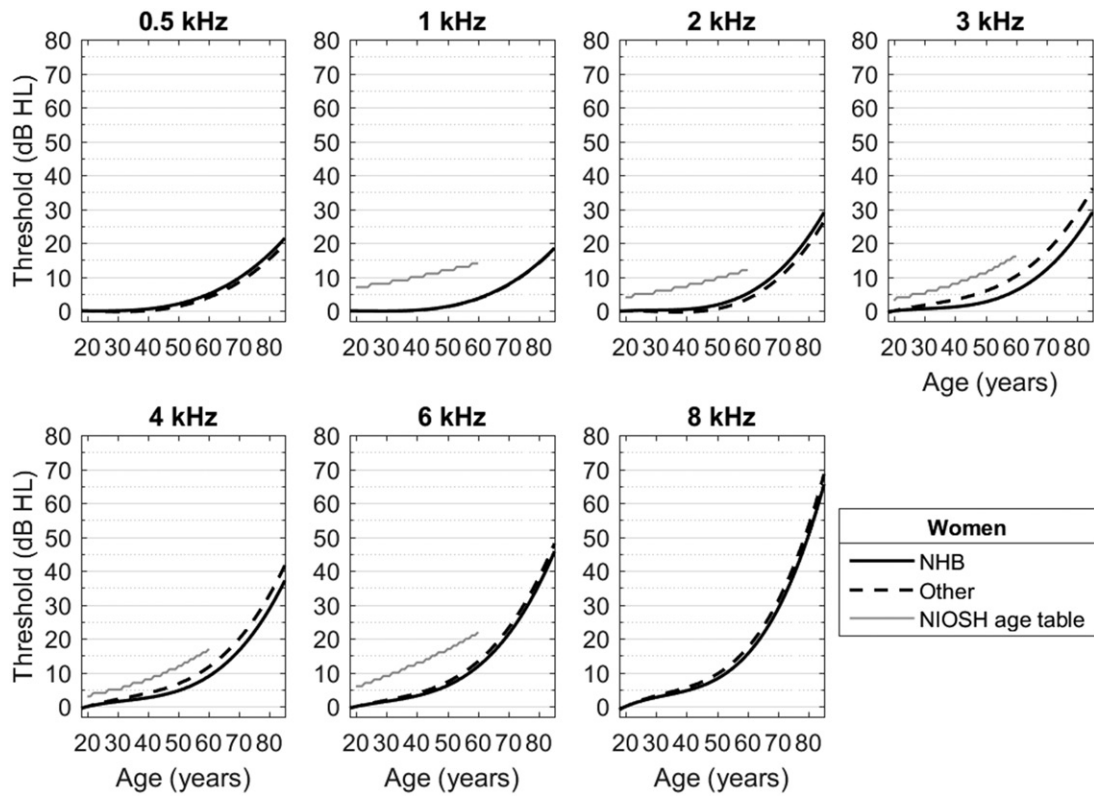


Figure 2. Comparison of 25th percentile cross-sectional trends in hearing sensitivity among women as a function of stimulus frequency, age, and demographic group. Black curves represent trends for the non-Hispanic Black (NHB) group (solid line) and other race/ethnicities (dashed line). The grey line represents the corresponding NIOSH age table.

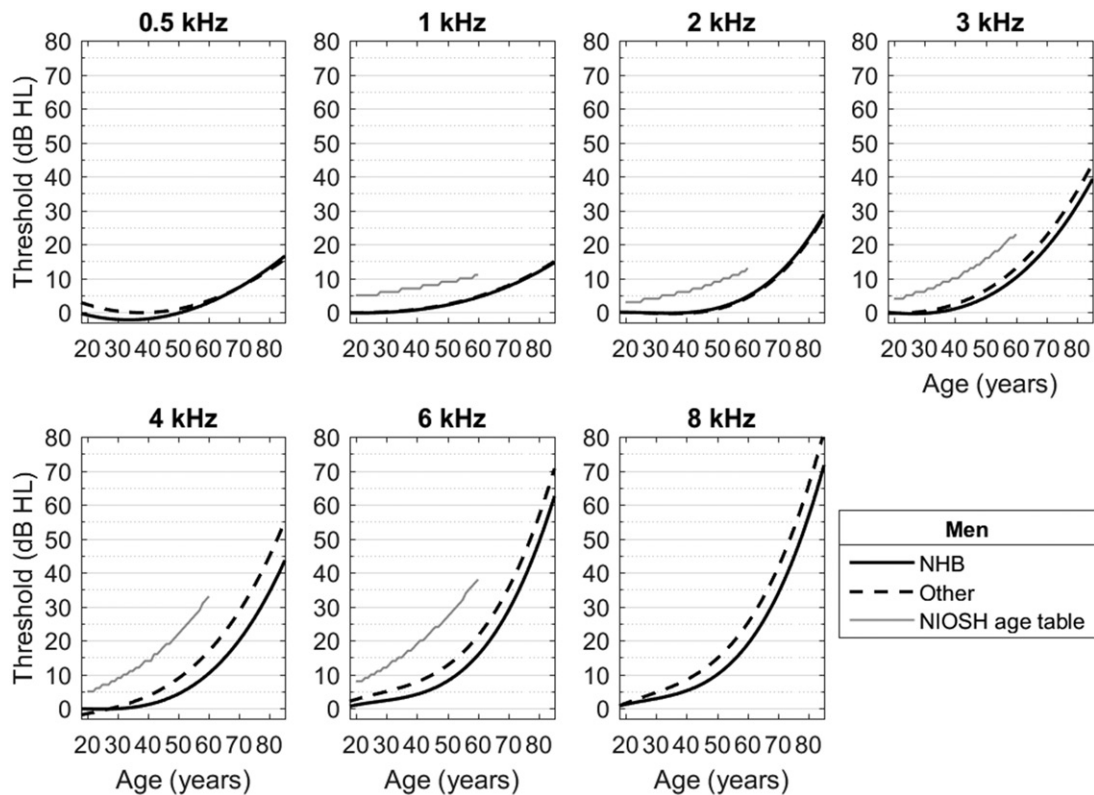


Figure 3. Comparison of 25th percentile cross-sectional trends in hearing sensitivity among men as a function of stimulus frequency, age, and demographic group. Black curves represent trends for the non-Hispanic Black group (solid line) and other race/ethnicities (dashed line). The grey line represents the corresponding NIOSH age table.

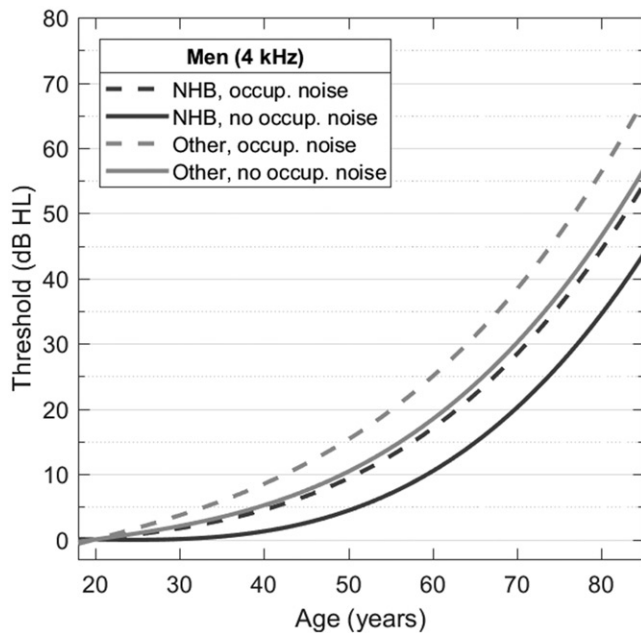


Figure 4. Cross-sectional trends in hearing sensitivity (25th percentile) for men at 4 kHz as a function of age and demographic group. Solid lines represent fitted quantile regression curves for men with no significant occupational noise exposure who identify as non-Hispanic Black race/ethnicity (black curves) and other than non-Hispanic Black race/ethnicity (grey). Dashed lines represent regression curves for men reporting at least three months of occupational noise exposure who identify as non-Hispanic Black (black curves) and other than non-Hispanic Black race/ethnicity (grey). Typical differences associated with occupational noise are negligible among the youngest adults and increase to approximately 10 dB in the oldest age groups. The magnitudes of race/ethnicity differences tend to be greater than those for occupational noise, leading to an expectation of better hearing among occupationally-exposed people who identify as non-Hispanic Black race/ethnicity than people who identify as other than non-Hispanic Black race/ethnicity with no occupational exposure.

thresholds at 0.5 kHz between the ages of 18 and 35 for men, which we considered an artefact of influential cases at younger ages on the curvilinear trend functions rather than as a real improvement in hearing sensitivity during early adulthood. This artefact has been corrected in [Supplementary Appendix B](#) by replacing the declining values with increased age with the lowest value, yielding no age-related change during young adulthood. For example, if the trend between ages 18 and 23 at 1 kHz declined from an expectation of 1 dB HL at age 18 to -1 dB HL at age 23, the values at ages 18 through 22 were replaced with -1 dB HL.

The 25th percentile cross-sectional trends were markedly different for people identifying as Non-Hispanic Black (NHB) relative to the other race/ethnicity categories (e.g. Non-Hispanic White (NHW), Mexican American (MA), Other Hispanic (HI)). The differences were commonly in the direction of better hearing thresholds as a function age among people with Non-Hispanic Black race/ethnicity. These race/ethnicity differences were significant for both genders, and were smaller among women ([Figure 2](#)) than men ([Figure 3](#)). The largest differences related to race/ethnicity were often found at stimulus frequencies above 2 kHz.

In addition to significant main effects terms in the models, multiplicative (i.e. effect modifications, interaction) effects were also observed as a function of age for the race/ethnicity and occupational noise exposure factors. The consequence of these multiplicative effects was to increase the magnitude of differences between race/ethnicity groups and occupational noise exposure

groups as a function of increased age. The race/ethnicity differences are observable in [Figures 2 and 3](#).

Taken together, differences in cross-sectional trends across race/ethnicity and occupational noise exposure ([Figure 4](#)) revealed that people identified as Non-Hispanic Black men with occupational noise exposure would be expected to have better hearing sensitivity than other men having no significant occupational noise exposure. This implies that, although occupational exposure was associated with poorer hearing in both race/ethnicity groups, this difference tended to be outweighed by the weaker cross-sectional trend toward worse hearing with age among those reporting NHB race/ethnicity. This difference is greatest in the high frequencies.

Validation with longitudinal data

The 25th percentile cross-sectional trends described above provided a close correspondence with the central tendency of longitudinal changes among men in the FDNY occupational database ([Figure 5](#)). Differences between the median longitudinal changes and predictions were 5 dB or less for both ears, all stimulus frequencies, and across categories of years of service.

The distributions of age-adjusted changes as a function of stimulus frequency were approximately symmetrical about the median through 2 kHz, and were skewed at frequencies of 3 kHz and above. The 10th percentile age-adjusted changes across audiometric stimulus frequencies ranged between apparent improvements of 5 to 15 dB, whereas the 90th percentile age-adjusted changes increased with stimulus frequency, with a 40-dB decline in hearing sensitivity at 8 kHz in the group with more than 30 years of service. This pattern of results is consistent with expectations from an exposed group of people with a wide range of susceptibility to noise damage.

Discussion

These results indicate that the 1970s-era NIOSH age adjustment tables used in U.S. regulations do not appear to represent contemporary trends in age-related changes in hearing sensitivity. The NIOSH age adjustment tables are often referred to as “age corrections” and are implemented in the U.S. OSHA hearing conservation amendment (OSHA 1983) and in other U.S. federal regulations, but they do not appear to reflect current age-related hearing changes, even at the group level.

The NIOSH age adjustment tables overestimate the typical effects of age, do not span the necessary range of ages for noise-exposed workers, and do not account for established differences in hearing sensitivity for groups of people identifying with Non-Hispanic Black race/ethnicity. Overestimation of the effects of age can compromise the effectiveness of hearing conservation programmes by leading programme managers to mistakenly attribute incident hearing loss to age. A reduced likelihood of detecting incident occupational hearing impairment leads to negative health outcomes for workers and reduced employer returns on investments in hearing conservation programmes.

The extension of the age adjustments beyond age 60 can resolve the long-standing problem of obtaining age-adjusted changes in hearing sensitivity for older workers. At present, age adjustments for workers over the age of 60 are calculated as if the workers were 60 years old, and the age trends observed in the present study demonstrate accelerating changes in hearing sensitivity in this age range ([Figures 2 and 3](#)). The limited range

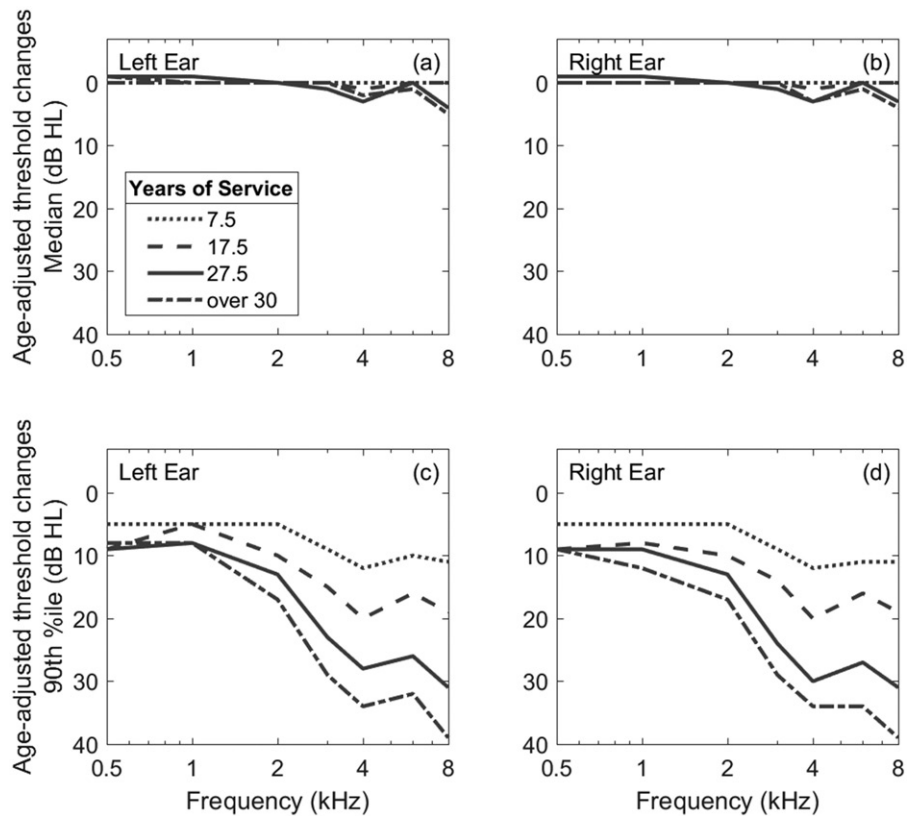


Figure 5. Age-adjusted threshold changes for men as a function of frequency and years of service. Data were taken from a large database of noise-exposed workers, five percent of whom were identified as having non-Hispanic Black race/ethnicity. Years of service were represented as midpoints of 5-year categories, with missing categories (e.g. 12.5 years) not presented here in order to preserve figure clarity. Upper panels (a and b) represent median changes; lower panels (c and d) represent 90th percentiles. Median changes after applying population-based age-adjustment tables from the present study were less than 5 dB, while the upper tail of the distribution (lower panels) showed significant declines in hearing sensitivity.

of ages in the original NIOSH tables facilitates under-allocation of observed changes to age in older workers.

The application of age adjustments appropriate for other race/ethnicity groups to Non-Hispanic Black men facilitates the overestimation of observed changes to age in this group. As shown in Figure 4, men working in occupational noise and identifying with NHB race/ethnicity tend to have better hearing sensitivity at older ages than men without occupational noise exposure who identify with other race/ethnicity categories. The results of this study imply that, if age adjustments are used, separate adjustments are needed for people identifying with NHB race/ethnicity.

The age adjustment tables proposed by Dobie and Wojcik (2015), as mentioned in the introduction, overestimate the cross-sectional age trends observed in the present study (Figure 6), and therefore would also provide a poor match to the longitudinal changes in hearing among noise-exposed workers. At age 20, the Dobie and Wojcik (2015) tables differ from the present study by approximately 4 dB. The difference grows steadily with age and reaches a 14–15 dB difference at age 75. This observation is not surprising, given the use of median cross-sectional trends in their NHANES curves, and the direct use of the original NIOSH tables in their hybrid method. At age 60, the difference is approximately 12 dB. The 8-dB difference in the slope of the 2, 3, and 4 kHz average across this age range is significant because users of the Dobie and Wojcik (2015) age adjustment table across this age range would subtract an additional 80% of the 10 dB criterion change for a reportable standard threshold

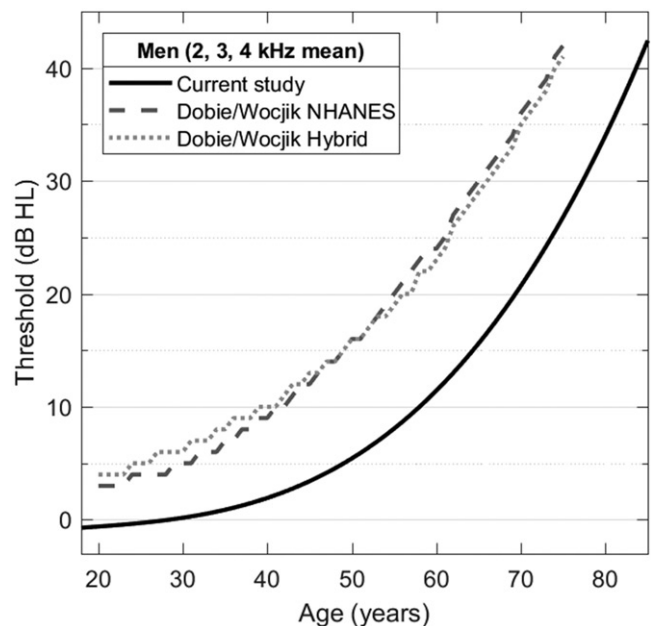


Figure 6. Comparison of current cross-sectional study results for men who identify as other than non-Hispanic Black race/ethnicity with Dobie and Wojcik (2015) (see text for additional information). Horizontal axis represents age in years, vertical axis represents expected threshold. NHANES results from Dobie and Wojcik are based on interval means from NHANES 1999–2006 cycles. Hybrid results represent NIOSH age adjustment tables through age 60, and fitted NHANES 1999–2006 interval means above 60.

shift (STS) defined in the OSHA hearing conservation amendment (29 CFR 1910.95), requiring an 18 dB change in average hearing sensitivity to reach the 10 dB shift mandated by the regulation. This type of error prevents employers from detecting overexposure to noise or ineffective hearing conservation programmes, which jeopardises worker health and reduces returns on investments in worker safety.

The present studies neither resolve nor minimise the validity of the NIOSH recommendation against the application of age adjustments to individual audiograms for significant threshold shift calculations (NIOSH 1998, p. 59–60). The present studies neither resolve nor minimize the validity of the NIOSH recommendation against the application of age adjustments to individual audiograms for significant threshold shift calculations (NIOSH 1998, p. 59–60). The results of these studies show that the use of the 1970s-era NIOSH age adjustments do not represent contemporary longitudinal changes in hearing sensitivity at the individual or group level.

Biases and limitations

The population-based age adjustment tables in this study were developed using hearing thresholds from a large sample and were analysed to yield results representing the non-institutionalised U.S. population. The population-based age adjustments were then applied to a large longitudinal database of noise-exposed workers. The finding that the median age-adjusted changes in hearing threshold were within 5 dB of the 25th percentile cross-sectional trend indicates that the population-based age adjustments derived from NHANES data provide a more accurate expectation of longitudinal changes for men at the group level.

However, the possibility remains that expectations that have been developed on the basis of cross-sectional trends might contain birth cohort effects, and those effects could change comparatively rapidly. For example, cross-sectional trends in hearing sensitivity as a function of age differed between the NHANES 1999–2004 cycles and the 2011–2012 cycles (Hoffman et al. 2017). Although these differences could be associated with changes in noise exposure profiles across birth cohorts, it is not known that the trend toward better hearing sensitivity at the population level has matured fully. It is important to recognise that future updates to the NIOSH age tables should be considered periodically to ensure that they remain an accurate representation of expected changes in hearing sensitivity with age.

The use of separate age adjustment tables based on gender and race/ethnicity requires ascertainment of these demographic characteristics. The requirement to ascertain gender has been present in all current U.S. regulations regarding hearing conservation, but race/ethnicity information has not been needed due to the lack of appropriate tables. Transgender or gender non-conforming people report hearing trouble at rates higher than women, based on analyses of data for hearing trouble from the 2016 and 2017 Behavioural Risk Factor Surveillance Survey (<https://www.cdc.gov/brfss/index.html>) (Flamme and Deiters 2019, unpublished report), which suggests that the use of tables for women would not be appropriate for this demographic group. In the event of absent information regarding gender or race/ethnicity or other circumstances (e.g. workers who do not conform to a specific gender or racial/ethnic category), three approaches might be taken. It would be most conservative and protective for the worker to forego age adjustment when age and/or race/ethnicity are unknown. A second alternative would be to apply the tables for women and/or people identifying as

non-Hispanic Black in order to reduce the possibility of overestimating the effects of age. Finally, based on known gender and race/ethnicity distributions of noise-exposed workers in a specific industry, it could be highly likely that a worker for whom gender and race information is unavailable is male and of “other” race/ethnicity, thus the age adjustment tables for men or for the “other” race/ethnicity category might be used.

One significant limitation of this study was that the longitudinal data compared with the cross-sectional trends were drawn from a group with occupational exposure to noise and other ototoxins. These exposures would be expected to produce changes in hearing over time that include changes due to excessive noise, ototoxin exposure and age; therefore the age adjustments produced in this study might still over-estimate the inexorable changes in hearing due solely to age. In addition, the longitudinal study group included only men and the preponderance of these were identified with non-Hispanic White race/ethnicity. We would prefer a comparison against a longitudinal cohort containing large numbers of unexposed men and women of all race/ethnicity backgrounds. However, a suitable dataset is not available, so we regard the population-based tables presented here as an upper limit on the central tendency of age effects. Men identified with non-Hispanic White race/ethnicity show the greatest cross-sectional change in hearing sensitivity with age (Supplementary Appendices A and B). Slower rates of longitudinal change in hearing sensitivity among people identified with non-Hispanic Black race/ethnicity were observed in the longitudinal cohort used in this study (Flamme et al. 2019). Together, the close match of the population-based tables to median longitudinal changes and the consistent direction of race/ethnicity differences between the cross-sectional and longitudinal data for men suggest that the population-based tables are substantially more accurate than the NIOSH tables used in current U.S. regulations. The age adjustment values returned by the NIOSH tables overestimate for the effects of age to a greater degree (Figures 2 and 3) and do not accommodate race/ethnicity differences.

Conclusion

The present study was informed by the limitations inherent in the original NIOSH tables [see NIOSH comments to the FRA (2006)] and illustrates the need for updated age adjustment tables for use in hearing conservation programmes that apply age adjustments. The NHANES-derived tables were based on nationally-representative 25th percentile cross-sectional trends and account for known differences in hearing sensitivity associated with gender and race/ethnicity. The population-based tables provided a good match to the median longitudinal changes observed in a large population of exposed men with work histories up to and beyond 30 years of service. Continued application of the original NIOSH age tables, which have been implemented in current U.S. regulations, can be expected to produce an over-estimation of the effects of aging and potentially produce an underestimation of the effects of occupational exposure.

Age adjustment is permitted but not required under current OSHA, MSHA, and FRA noise regulations (OSHA 1983; MSHA 1999; FRA 2006). NIOSH continues to recommend against age correction (NIOSH 1998). However, if age adjustments are to be used, the population-based tables derived in this study provide a more accurate estimate of expected age-related hearing changes in the current U.S. population. Regulatory agencies should consider adoption of population-based tables for compliance purposes. However, even without regulatory adoption, population-

based tables could be a useful resource for hearing loss prevention professionals. The tables could serve as a comparison dataset for evaluating thresholds in various noise-exposed populations. These tables could furnish one source of information during professional evaluation of significant threshold shifts that might be associated with occupational exposure. Utilisation of age adjustment tables that reflect the hearing sensitivity of the current U.S. adult population and account for varying hearing loss trajectories by age and race/ethnicity should improve hearing loss prevention efforts and be an important tool for preventing occupational hearing loss.

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Disclosure statement








No potential conflict of interest was reported by the authors.

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