Use of historical data and a novel metric in the evaluation of the effectiveness of hearing conservation program components

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Accepted 30 September 2010
Published Online First 7 November 2010

ABSTRACT

Objectives To evaluate the effectiveness of hearing conservation programs (HCP) and their specific components in reducing noise-induced hearing loss (NIHL).

Methods This retrospective cohort study was conducted at one food-processing plant and two automotive plants. Audiometric and work-history databases were combined with historical noise monitoring data to develop a time-dependent exposure matrix for each plant. Historical changes in production and HCP implementation were collected from company records, employee interviews and focus groups. These data were used to develop time-dependent quality assessments for various HCP components. 5478 male (30 427 observations) and 1005 female (5816 observations) subjects were included in the analysis.

Results Analyses were conducted separately for males and females. Females tended to have less NIHL at given exposure levels than males. Duration of noise exposure stratified by intensity (dBA) was a better predictor of NIHL than the standard equivalent continuous noise level (L_{eq}) based upon a 3-dBA exchange. Within this cohort, efficient dBA strata for males were <95 versus ≥95, and for females <90 versus ≥90. The reported enforced use of hearing protection devices (HPDs) significantly reduced NIHL. The data did not have sufficient within-plant variation to determine the effectiveness of noise monitoring or worker training. An association between increased audiometric testing and NIHL was believed to be an artifact of increased participation in screening.

Conclusions Historical audiometric data combined with noise monitoring data can be used to better understand the effectiveness of HCPs. Regular collection and maintenance of quality data should be encouraged and used to monitor the effectiveness of these interventions.

What this paper adds

- This study describes an alternative measure for cumulative noise exposure over a period of years and demonstrates that, for these data, duration of noise exposure divided into intensity strata was a better predictor of noise-induced hearing loss (NIHL) than the standard equivalent continuous noise level (L_{eq}) based upon a 3-dBA exchange rate.
- A methodology for evaluating the quality of components of hearing conservation programs (HCP) and their contribution to reducing NIHL over time is presented.
- The HCPs studied had varied levels of implementation for specific components across time and plants.
- This study demonstrates that females tended to have less occupational NIHL at given exposure levels than males in the studied plants.
- Additional evidence on the effectiveness of hearing conservation programs to reduce occupational exposure to noise and associated NIHL is presented; specifically, enforced use of hearing protection devices was effective in reducing NIHL at the studied plants.

INTRODUCTION

Noise-induced hearing loss (NIHL) remains a pervasive occupational condition despite decades of regulation and data collection required by the Department of Labor noise standard[1] and its Occupational Safety and Health Administration (OSHA) Occupational Noise Exposure, Hearing Conservation Amendment (HCA).[2] The HCA established permissible exposure levels (90 dBA with 5-dBA exchange rate) and mandated hearing conservation programs (HCPs) requiring annual audiometric testing for workers exposed to noise levels above 85 dBA as a time-weighted average (TWA).[3] While OSHA provided clear guidance on how to monitor compliance at the individual level, no guidance was provided on how to use group data in the evaluation of an HCP. After 27 years of the HCA, an abundance of historical data exists, yet publications evaluating HCPs are scarce.

Given the resources involved in these HCPs, evaluations are needed, but no generally accepted study design, analytical approach or metric for noise exposure and hearing loss exist. Using audiometric pure-tone threshold levels, hearing loss can be viewed as a continuum or as a dichotomous variable where averaged thresholds are compared to a boundary defining a significant threshold shift. No consensus exists on the best definition.[4]

Results from long-term studies on the issue either do not support or provide only weak evidence for HCP effectiveness.[5–7] A recent Cochrane Review of interventions to prevent occupational NIHL identified 21 studies which met the review's eligibility criteria with 15 concerning

 Occup Environ Med 2011;68:510–517. doi:10.1136/oem.2009.053801

HCPs.[8] The authors concluded that evidence on the effectiveness of hearing protection devices (HPDs) and HCPs was contradictory. Comparing exposed workers who used HPD and unexposed workers, studies found anywhere from no difference to three- or fourfold increases in NIHL among those exposed. Four studies attributed these disparities to variability in the implementation of various HCP components across and within industries.[9–12] Most studies lack sufficient information to evaluate how specific components of an HCP contribute to the prevention of hearing loss.

Two issues need to be clarified to promote audiometric database analysis in evaluating HCP effectiveness: whether and how historical HCP data (with its flaws) can be used to reconstruct noise levels and the quality of implementation of HCP components; and identification of analytical approaches for historical HCP data. The objective of this study was to evaluate the usefulness of historical HCP data collected through mandated audiometric testing, noise surveillance and record keeping for measuring associations between the implementation quality of HCP components over time and NIHL.

METHODS

This study uses information collected by NIOSH between 1998 and 2000 at three unionised plants in the USA, including one food processing plant (plant 1) and two automotive plants — one a stamping plant which manufactured floor pans, doors, hoods and fenders (plant 2), and the other a chassis plant which manufactured parts such as rack and pinions, housings for pumps, gears, bolts and pistons (plant 3). Current and historical data on HCP implementation and management were collected at each company through audits of company records and policies, interviews with HCP administrators, and focus groups with long-term hourly employees and first line supervisors.[13] This information was combined with data from longitudinal audiometric testing records, historical noise surveys and more recent task-based noise exposure surveys to construct concurrent retrospective timelines of qualitative variations in HCP implementation, quantitative changes in noise exposure, and hearing thresholds for each subject. This paper analyses these data from 1970 through 1999 to identify components of HCP implementation effective in preventing occupational NIHL.

Retrospective noise exposure assessment

Recent and historical noise monitoring data were used to assign 8 h TWA noise exposure values to various tasks and, through job analyses, to jobs listed in the work histories.[14] The resulting exposure matrix files defined time-dependent noise exposures for workers at each plant. Area noise surveys in 1983 and 1994 and a 1997 NIOSH-sponsored task-based noise survey were used to assign job specific noise levels for plant 1 (based on stable production processes, volumes and equipment reported by focus groups,[13] walk-through observations of noise sources and review of plant records). Area noise surveys conducted in 1970—1971 and 1985—1986, with additional task-based noise exposure assessments in 1991, 1995 and 1998 were used for plant 2, while area noise surveys conducted in 1971 and task-based noise exposure assessments conducted in 1990, 1992, 1995 and 1997 were used for plant 3.

Audiometric data

The 1970—1999 study period was defined by the availability of audiometric data. However, each plant did not contribute data over the entire period. Audiometric records were available for plant 1 from 1984 to 1999, for plant 2 from 1978 to 1999, and for plant 3 from 1970 to 1999. The initial number of employees included and audiometric tests conducted by plant were 1879 (20 390), 4818 (39 303) and 4683 (20 635), respectively.

Audiograms were screened for acceptability based upon threshold variability across adjacent frequencies, cross-ear and cross-consecutive audiograms using an 'Expert System' program developed by NIOSH.[15] Flagged audiograms were reviewed for inclusion by an experienced audiologist. Because subjects with deteriorating hearing have more problems successfully responding to audiometric signals (eg, missing values may indicate no response at the highest dB level tested), exclusion of all incomplete audiograms can introduce bias. Thus, when a reasonably clear interpretation of audiometric results was possible, missing values were replaced with estimates derived from the immediately preceding and following audiograms. The number of edited audiograms by plant were 181 (0.9%), 172 (0.4%) and 106 (0.5%), respectively. The number of audiograms found to be unacceptable by the audiologist and removed from the analysis were 676 (3.3%), 1086 (2.8%) and 309 (1.5%), respectively.

Audiometric hearing thresholds

To maximise sensitivity and specificity to NIHL, hearing thresholds were defined as the average of pure-tone audiometric thresholds across three frequencies (3, 4 and 6 kHz) and both ears. The choice of frequencies is based upon the classic 'notch' in audiograms of noise-exposed subjects. Furthermore, NIHL is usually bilateral.[16] Change in hearing (delta threshold) was measured as change in audiometric threshold from each subject's first (baseline) audiogram to each subsequent audiogram to capture the chronic nature of NIHL. Delta threshold was treated as a continuous variable to provide maximum information for modelling HCP effectiveness.

HCP component measures

HCP compliance with standards set by the HCA were previously evaluated along seven dimensions: (1) training and education; (2) noise monitoring; (3) engineering and administrative controls; (4) audiometric testing and surveillance; (5) medical referral; (6) HPD use; and (7) administrative and record keeping procedures.[13] Limited historical information collected during focus groups allowed for time-dependent evaluation of three HCP components: (1) HPD use; (2) noise monitoring; and (3) worker training. Dichotomous ('better' vs 'poorer') quality ratings based upon group recall are necessarily crude.

Our HPD quality measure, based upon estimated percentage of noise-exposed employees using HPD, could not capture more nuanced criteria such as proper fitting. Better quality status was assigned for ≥50% compliance. Plant 1 was rated as poorer from its entry into the study in 1984 through 1989 and better after that. Plant 2 was rated poorer from 1970 to 1979, better from 1980 to 1989, mixed (better for hourly and poorer for salaried employees) from 1990 to 1994 and poorer thereafter. Plant 3 was rated poorer from 1978 to 1979, better from 1980 to 1994 and poorer thereafter.

Noise monitoring quality was rated better if any monitoring and worker input was reported by the focus groups. Only plant 3 had a better quality program, which was true from its entry into the study in 1978 to the end. Plants 1 and 2 had poorer quality programs throughout.

Worker training had only minimal compliance at these plants (even the best relied on handouts or videos without any follow-up). Thus, any reported effort was assigned better quality status. Plant 1 quality was poorer from 1984 to 1989 and better thereafter. Plant 2 quality was poorer throughout, while plant 3 was poorer from 1978 to 1989 and better thereafter.

A fourth component, audiometric testing program quality, was based upon the average number of days between consecutive audiograms in each plant's audiometric database. Better quality was assigned to averages of <500 days (365 days being in full compliance). Information on the adequacy of noise exposure control both before and during audiometric testing was not available. Plant 1 quality was better from 1984 to 1989, poorer from 1990 to 1994 and better thereafter. Plant 2 was poorer from 1970 to 1984 and better thereafter. Plant 3 was poorer form 1978 to 1984, better from 1985 to 1989 and poorer thereafter.

Study population

Subjects were defined by comparing work history and audiometric files. Only audiograms administered within the time period of each employee's work history (including a 90-day pre-employment period) were included in the study. All plant 1 audiograms met these criteria. However, plants 2 and 3 were part of a large company with potential worker migration, and only 18 240 (46.4%) of plant 2 audiograms and 7999 (38.8%) of plant 3 audiograms qualified for inclusion. Subjects with only one qualified audiogram could not have threshold changes calculated and were excluded. These data restrictions defined a total of 5774 male subjects with 33 473 non-baseline observations (based upon 39 247 audiograms) and 1061 female subjects with 6375 observations (based upon 7436 audiograms).

Review of the qualifying audiometric data demonstrated considerable swings in audiometric thresholds — including improvement — which were not consistent with NIHL. This unwanted variability has been reported elsewhere,[17] and could be attributed to temporary threshold shifts, to poor testing conditions or to individual test taking characteristics. As excess variability was confined to a small number of subjects, subjects whose binaural hearing threshold improved by 15 dB or more from either their baseline or immediately preceding audiogram were defined as 'highly variable' responders and eliminated from analysis. Thus, 194 (149 male/45 female), 119 (112 male/7 female) and 39 (35 male/4 female) employees from the three plants, respectively, were eliminated from the analyses (5.1% of male and 5.3% of female subjects).

The final male study cohort included 5478 subjects with a total of 30 427 observations: 1152 (21%) subjects and 11 529 (38%) observations from plant 1; 2655 (48%) subjects and 13 307 (44%) observations from plant 2; and 1671 (31%) subjects and 5591 (18%) observations from plant 3. The final female study cohort included 1005 subjects with a total of 5816 observations: 415 (41%) subjects and 4138 (71%) observations from plant 1; 401 (40%) subjects and 1290 (22%) observations from plant 2; and 189 (19%) subjects and 388 (7%) observations from plant 3.

Calculating exposure variables

Exposure variables, including noise exposure (except for L_{eq}) and its attenuation by HCP quality, are created using duration of work within various categorical groupings. Values for these categorical groupings vary by job and time period. One set of calendar time periods determine level of noise exposure within a given job title, while another set determine the various HCP quality ratings within each plant. To calculate these variables, when a job spans a boundary between any of these categorical groupings, it is divided into two or more segments so that each segment fits into only one set of categories. Similarly, when any job segment spans an audiometric test for the subject, that segment is subdivided into two segments at the date of testing.

Each subject enters the study at the date of their first valid (baseline) audiogram, and exposure duration variables are calculated from that date to the date of each successive audiogram by simply adding the duration of each job segment within that time span to the appropriate categorical variables for that job segment. These variables are cumulative across all successive audiograms, and are not set to zero after each audiogram.

Statistical methods

Generalised estimating equations (GEEs), which account for the correlated structure of longitudinal data, were used to fit all models (Proc GENMOD procedure in SAS v 9.1). GEEs provide consistent and unbiased estimation of parameters' standard errors and are widely applied to estimate linear and non-linear models for data of correlated and clustered structure.[18] In our analyses, data were considered correlated with respect to both subject and plant. Separate analyses were conducted for male and female workers.

Modelling change in binaural hearing thresholds

The statistical model used for evaluating NIHL examines the association between change in binaural hearing thresholds and cumulative occupational noise exposures controlling for age, plant and other factors (equation 1). Information on noise exposures from other employment and non-occupational sources (military exposures, music, etc), as well as medical information that might impact hearing thresholds, were not available for analysis. Race (Caucasian vs non-Caucasian) was not a significant predictor. For each subject, every valid audiogram (except the baseline) provided a data point for analysis.

$$\begin{aligned}\Delta HT_t =& \beta_0 + \beta_1 Plant2(0/1) + \beta_2 Plant3(0/1) + \beta_3 HT_0 \\ &+ \beta_4 Age_t + \beta_5 CumNoiseExp_t \end{aligned} \quad (1)$$

where: ΔHT_t is change in hearing threshold from baseline at time t (test) in dB, $plant2/3$ is 1 if the subject is employed at the indicated plant, otherwise 0, HT_0 is baseline hearing threshold in dB, Age_t is age at time t (test) in years, and $CumNoiseExp_t$ is measure of cumulative occupational noise exposure at time t in years.

In preparation for modelling NIHL, two additional analyses were conducted, to define a metric for cumulative occupational noise exposure and to evaluate the linearity of NIHL over time.

Cumulative occupational noise exposure metric

A standard metric for cumulative noise exposure was compared to a duration of exposure metric to determine which best explained NIHL in this study. The standard cumulative noise exposure metric is the 'equivalent continuous noise level' or L_{eq} defined as:

$$\begin{aligned}&\text{Time-Weighted Cumulative Noise Exposure} = L_{eq} \\ &\quad = qLog_{10}\left[\sum 10^{LE_i/q} t_i\right]; \end{aligned} \quad (2)$$

where q is the exchange rate or 'decibel value multiplier', LE_i is dBA sound level assigned to the ith job, and t_i is duration in years of the ith job (where the duration in the last job would be truncated at the time the audiometric test was performed).[19]

When q is set to 10 an increase of 3 dBA is equivalent to a doubling of exposure duration in the above equation. NIOSH uses this exchange rate because a change of 3 dBA represents a doubling of sound pressure and this rate creates a sound pressure-years equivalency (2 years of exposure at 90 dBA would be equivalent to 1 year of exposure at 93 dBA). L_{eq} explicitly assumes that noise has a linear effect across all sound pressure levels, an idea that is not universally accepted. Furthermore, the equivalency assumption makes it susceptible to inaccuracies in measurement, especially with respect to historical reconstruction of dBA-exposure levels.

An alternative metric was tested using cumulative duration of occupational exposure stratified by the TWA noise intensity levels (<80, 80 to <85, 85 to <90, 90 to <95, ≥95 dBA). This metric gives more weight to exposure duration and allows the data to independently determine the exposure–effect relationship for each noise level. A similar, but less detailed approach, has been taken in a recent Canadian study.[20]

Linearity of NIHL over time

The linearity of the impact of occupational noise exposure on NIHL over time was evaluated only for the stratified duration of exposure measures described above. This was accomplished by dividing each stratum of noise exposure duration into two segments and testing the improvement in model fit. This 'spline' approach was evaluated for various 1-year interval cut-points.

Modelling HCP implementation quality

Employment duration within estimated 'better' quality programs for each of the four defined components of HCP implementation were used to evaluate their impact on NIHL. The HCP quality variables were introduced independently. Thus the final equation for evaluating HCP component quality is:

$$\Delta HT_t = \beta_0 + \beta_1 Plant2(0/1) + \beta_2 Plant3(0/1) + \beta_3 HT_0 + \beta_4 Age_t + \beta_5 CumNoiseExp_t + \beta_6 HCP_{qt} \quad (3)$$

where equation 3 variables have the same interpretation as in equation 1, with the addition of HCP_{qt} representing years in a 'better' quality program at time t for one of the four HCP quality components.

RESULTS

Population statistics for the variables used in these analyses are shown for males and females in table 1. These include subject demographics (race and age at entry), audiometric information (hearing at entry, change in hearing across audiograms – data shown for last audiogram, and number of audiograms), noise exposure duration (in years) across audiograms – data shown for last audiogram within several categories (total, up to or above 95/90 dBA for men/women, and up to or above 6 years for men only), the continuous equivalent noise level calculated for noise exposures across the entire study, and duration within better HCP program components (HPD use, audiometric testing, noise monitoring and worker training).

Plant 1 had the smallest worker population of the three plants and the most female workers. Its workers had on average approximately twice as many valid audiograms and were followed for almost twice as many years. Workers at this plant had more hearing loss at entry (higher baseline threshold), and larger changes in their hearing threshold than workers at the other plants.

The predominant noise exposures at plants 1 and 2 were in the 85 to <90 and 90 to <95 dBA categories, while workers at plant 3 spent only minimal amounts of time in areas with noise levels above 90 dBA (not shown). Female employees at plants 1 and 2 spent a higher proportion of their time in areas at or above 90 dBA than did their male counterparts. Based upon the L_{eq}, women had higher levels of noise exposure than men at plant 1, but lower levels at the other two plants.

Results for the basic NIHL model

The duration of exposure metric, even without stratification, was superior to L_{eq} for predicting NIHL in this cohort. Total duration of occupational noise exposure explained significantly more of the observed change in hearing threshold than did L_{eq}. With L_{eq} alone in the model, age at audiometric testing became more important. When both exposure measures were included, L_{eq} remained significant, but its actual impact on NIHL was negligible.

It has been argued that age is the more fundamental driver of hearing loss and duration of exposure 'steals' some of its variance through their high correlation. However, this cohort has substantial variation in age at baseline (table 1), and the correlation between age and duration is limited (males r=0.35; females r=0.58). Thus, stratified duration of exposure was selected as our metric.

The efficiency of 5 dBA stratification was evaluated. Among men, only the ≥95 dBA stratum differed significantly from overall duration. Among women, this was true for exposure at or above 90 dBA. Thus, cumulative noise exposure could be efficiently defined using only two intensity strata: exposures <95 and ≥95 dBA for men, and <90 and ≥90 dBA for women.

Evaluation for linearity of effect over time using the 'spline' approach demonstrated that the effect of noise exposure on NIHL decreased over time among males, with 6 years being the most efficient breakpoint for noise exposures both less than or greater than 95 dBA. However, no such decrease among females was observed. The resulting NIHL models for males and females are shown in table 2.

Model coefficients represent the contribution to hearing loss (in average binaural dB change at 3, 4 and 6 kHz) of their respective variable. The noise exposure variables represent the yearly contribution of occupational noise exposure to NIHL, and it can be seen that, while hearing continues to decline among males after 6 years of exposure, the rate of decline decreases. As negative coefficients indicate a protective effect, subjects with higher baseline hearing loss tend to experience less NIHL.

The two gender-specific models, while different, show similar trends. Differences in the intercept and plant variables may be due to the different distributions of exposures between males and females at the three plants. However, the effect of age (at testing) is the same (within rounding differences) for both genders. Finally, while adjustments need to be considered for the different exposure categories used, it seems clear that females tend to have less NIHL at given exposure levels than males.

HCP models

A priori expectations were that 'better' HCP implementation would protect against NIHL, and that this would be true for each HCP component. This expectation would be exhibited in the analysis as a negative coefficient for each HCP_{qt} variable, demonstrating that longer duration in a 'better' program would subtract (protect) from the effect of noise exposure. The four HCP components yielded varied results.

Our analyses demonstrates that *HPD use* provided a significant reduction in NIHL for both genders (table 3). Comparing tables 2 and 3, it is clear that including HPD use in the model resulted in substantially higher coefficients for the occupational noise exposure variables. In this model, the noise coefficients represent NIHL among workers in a poorer HPD use program

Table 1 Male and female study population statistics, by studied plant

Population statistic	Plant 1 Mean	Plant 1 SD	Plant 2 Mean	Plant 2 SD	Plant 3 Mean	Plant 3 SD	Total Mean	Total SD
Males								
No. of employees	1152	2655	1671	5478				
% Caucasian	99%	81%	83%	86%				
Baseline age (years)	36.4	9.5	39.1	11.2	41.2	11.0	39.2	10.9
Audiogram information								
Baseline threshold (3, 4 and 6 kHz, both ears)	28.4	18.8	26.7	19.3	26.0	18.2	26.9	18.9
Delta threshold — final audiogram (dB)	7.9	8.1	4.4	7.0	3.1	6.1	4.7	7.2
No. of audiograms/subject	11.0	3.6	6.0	4.1	4.4	2.7	6.6	4.4
Duration (in years at final audiogram) of occupational noise exposures for <95 dBA or ≥95 dBA and ≤6 years or >6 years								
Total duration of noise exposure	11.0	3.6	5.8	5.1	5.3	4.0	6.8	5.0
Duration at <95 dBA and ≤6 years	5.3	1.6	3.5	1.9	3.9	1.9	4.0	2.0
Duration at <95 dBA and >6 years	5.3	3.0	1.7	3.8	1.4	2.6	2.4	3.6
Duration at ≥95 dBA and ≤6 years	0.4	1.3	0.5	1.4	0.05	0.3	0.4	1.2
Duration at ≥95 dBA and >6 years	0.08	0.7	0.07	0.6	0.0	0.0	0.05	.5
Time-weighted cumulative noise exposure								
Equivalent continuous noise level (L_{eq})	99.7	5.3	96.3	5.6	92.5	5.2	95.9	6.0
Time-dependent HCP quality measures — duration (in years) of noise exposure while in 'better' quality programs								
HPD use — duration better	7.2	2.3	3.3	4.8	3.2	3.6	4.1	4.3
Audiometric testing — duration better	6.6	2.8	4.8	3.9	1.1	1.9	4.1	3.8
Noise monitoring — duration better	0.0	0.0	0.0	0.0	5.3	4.0	1.6	3.3
Worker training — duration better	7.2	2.3	0.0	0.0	4.2	2.6	2.8	3.4
Females								
No. of employees	415	401	189	1005				
% Caucasian	98%	65%	66%	79%				
Baseline age (years)	38.2	9.2	32.5	9.6	35.3	9.9	35.4	9.9
Audiogram information								
Baseline threshold (3, 4 and 6 kHz, both ears)	15.2	10.2	10.8	8.8	10.8	7.9	12.6	9.5
Delta threshold — final audiogram (dB)	5.1	7.0	1.6	4.2	1.2	5.0	3.0	5.9
No. of audiograms/subject	11.0	3.8	4.2	2.0	3.1	1.6	6.8	4.5
Duration (in years at final audiogram) of occupational noise exposures at <90 dBA or ≥90 dBA								
Total duration of noise exposure	10.9	3.6	3.4	2.0	3.4	2.3	6.5	4.7
Duration at <90 dBA	4.4	3.6	1.3	1.5	3.2	2.2	2.9	3.0
Duration at ≥90 dBA	6.5	3.9	2.0	1.5	0.2	0.6	3.5	3.7
Time-weighted cumulative noise exposure								
Equivalent continuous noise level (L_{eq})	101.2	4.2	94.8	3.8	90.0	4.2	96.6	5.9
Time-dependent HCP quality measures — duration (in years) of noise exposure while in 'better' quality programs								
HPD use — duration better	7.2	2.3	0.8	1.4	1.5	1.9	3.6	3.6
Audiometric testing — duration better	6.5	2.8	3.3	2.0	0.3	1.0	4.1	3.2
Noise monitoring — duration better	0.0	0.0	0.0	0.0	3.4	2.3	0.6	1.7
Worker training — duration better	7.2	2.3	0.0	0.0	3.1	1.9	3.6	3.7

HCP, hearing conservation program; HPD, hearing protection device.

rather than the average worker. Workers in a better HPD program have NIHL represented by adding the negative HPD use coefficient to the noise variable coefficients, which results in NIHL levels well below the average values shown in table 2.

Partial results for the *audiometric testing*, *noise monitoring* and *worker training* components are shown in table 4. Intercept and plant variable coefficients (not shown) changed with each HCP variable, reflecting variation in component quality by plant.

Table 2 Initial models for noise-induced hearing loss with stratified exposures by gender

Males (N=5478)

Parameter	Coefficient	SE	95% CI
Intercept	−1.96	0.27	−2.49 to −1.43
Plant 2	−0.39	0.18	−0.75 to −0.03
Plant 3	−1.02	0.20	−1.40 to −0.64
Individual characteristics			
Baseline threshold	−0.03	0.004	−0.04 to −0.02
Age at test	0.08	0.008	0.07 to 0.10
Noise exposure duration (in years)			
<95 dBA/≤6 years	0.60	0.02	0.56 to 0.65
≥95 dBA/≤6 years	0.82	0.08	0.67 to 0.97
<95 dBA/>6 years	0.52	0.02	0.48 to 0.56
≥95 dBA/>6 years	0.43	0.13	0.18 to 0.69

Females (N=1005)

Parameter	Coefficient	SE	95% CI
Intercept	−3.35	0.59	−4.50 to −2.20
Plant 2	1.23	0.26	0.71 to 1.74
Plant 3	0.92	0.39	0.16 to 1.68
Individual characteristics			
Baseline threshold	−0.05	0.02	−0.08 to −0.01
Age at test	0.08	0.02	0.05 to 0.11
Noise exposure duration (in years)			
<90 dBA	0.28	0.05	0.18 to 0.37
≥90 dBA	0.50	0.05	0.40 to 0.60

Table 3 Model for hearing protection device (HPD) use with stratified exposure by gender

Males (N=5478)					Females (N=1005)				
Parameter	**Coefficient**	**SE**	**95% CI**	**p Value**	**Parameter**	**Coefficient**	**SE**	**95% CI**	**p Value**
Intercept	−2.24	0.27	−2.76 to −1.71	<0.0001	Intercept	−3.47	0.60	−4.64 to −2.30	<0.0001
Plant 2	−0.04	0.18	−0.39 to 0.32	0.8470	Plant 2	1.27	0.26	0.75 to 1.79	<0.0001
Plant 3	−0.62	0.19	−1.00 to −0.24	0.0014	Plant 3	1.00	0.39	0.24 to 1.76	0.0101
Individual characteristics					Individual characteristics				
Baseline threshold	−0.03	0.004	−0.04 to −0.02	<0.0001	Baseline threshold	−0.05	0.02	−0.09 to −0.01	0.0055
Age at test	0.08	0.008	0.07 to 0.10	<0.0001	Age at test	0.08	0.02	0.05 to 0.11	<0.0001
Noise exposure duration (in years)					Noise exposure duration (in years)				
<95 dBA/≤6 years	0.77	0.03	0.71 to 0.82	<0.0001	<90 dBA	0.39	0.07	0.26 to 0.52	<0.0001
≥95 dBA/≤6 years	1.04	0.08	0.88 to 1.20	<0.0001	≥90 dBA	0.60	0.07	0.46 to 0.73	<0.0001
<95 dBA/>6 years	0.79	0.04	0.72 to 0.86	<0.0001					
≥95 dBA/>6 years	0.69	0.13	0.43 to 0.95	<0.0001					
Better HPD use	−0.31	0.03	−0.37 to −0.24	<0.0001	Better HPD use	−0.14	0.07	−0.27 to −0.01	0.0290

However, the coefficients for baseline threshold and age at audiometric testing (also not shown) remained unchanged (within rounding differences) from those shown in tables 2 and 3.

Results for *audiometric testing* (table 4) had a reversed pattern, where better quality audiometric testing was significantly associated with increased hearing loss (positive coefficient). This result may be due to the way audiometric testing quality was determined — through enforcement (frequency) rather than how well it was performed (in good sound booth after a period removed from noise exposure, results reviewed with subject, etc).

Noise monitoring was significantly associated with reduced hearing loss only among male subjects. However, these results are likely confounded by work location, as plant 3 had the only better rated noise monitoring program. There was a correlation between plant 3 and better noise monitoring of 0.77 (p<0.0001). This explanation is supported by the fact that there was virtually no change in the coefficients for the four noise exposure variables in this model to account for the protective effects of noise monitoring (as seen in the HPD use model).

The models for *worker training* showed no significant impact on NIHL among either gender. These results are consistent with the observation that none of the plants had acceptable implementation of worker training, and the distinction between poor versus better programs was minimal.

Attempts to model all HCP components simultaneously led to results that were not interpretable. This is likely due to the high number of duration variables (for both noise exposure and HCP quality) overlapping and dividing variance in unpredictable ways.

DISCUSSION

This study has demonstrated the feasibility of evaluating HCP effectiveness using typical historical data and evaluating specific components of these programs. Despite well documented problems with historical noise and audiometric testing data, our reconstruction of noise exposures, audiometric results and the impact across the first three decades of nationally mandated HCPs provided consistent and interpretable results predicting changes in binaural hearing thresholds at 3, 4 and 6 kHz. Our unique method of quantifying HCP component quality was limited by our inability to collect more detailed historic HCP

Table 4 Noise-induced hearing loss results for models of remaining hearing conservation program parameters and stratified exposure by gender

Males (N=5478)					Females (N=1005)				
Parameter	**Coefficient**	**SE**	**95% CI**	**p Value**	**Parameter**	**Coefficient**	**SE**	**95% CI**	**p Value**
Analysis for HCP component - audiometric testing									
Noise exposure duration (in years)									
<95 dBA/≤6 years	0.54	0.03	0.48 to 0.60	<0.0001	<90 dBA	0.13	0.06	0.01 to 0.24	0.0284
≥95 dBA/≤6 years	0.77	0.08	0.61 to 0.92	<0.0001	≥90 dBA	0.33	0.06	0.20 to 0.45	<0.0001
<95 dBA/>6 years	0.43	0.03	0.38 to 0.49	<0.0001					
≥95 dBA/>6 years	0.31	0.14	0.04 to 0.57	0.0241					
Better audiometry testing	0.13	0.03	0.06 to 0.19	0.0003	Better audiometry testing	0.33	0.07	0.19 to 0.47	<0.0001
Analysis for HCP component - noise monitoring									
Noise exposure duration (in years)									
<95 dBA/≤6 years	0.64	0.02	0.59 to 0.69	<0.0001	<90 dBA	0.29	0.05	0.19 to 0.39	<0.0001
≥95 dBA/≤6 years	0.83	0.08	0.67 to 0.98	<0.0001	≥90 dBA	0.50	0.05	0.40 to 0.60	<0.0001
<95 dBA/>6 years	0.53	0.02	0.49 to 0.58	<0.0001					
≥95 dBA/>6 years	0.43	0.13	0.18 to 0.68	<0.0008					
Better noise monitoring	−0.13	0.03	−0.20 to −0.07	<0.0001	Better noise monitoring	−0.15	0.15	−0.44 to 0.14	0.3050
Analysis for HCP component - noise monitoring - worker training									
Noise exposure duration (in years)									
<95 dBA/≤6 years	0.62	0.02	0.58 to 0.67	<0.0001	<90 dBA	0.32	0.07	0.19 to 0.46	<0.0001
≥95 dBA/≤6 years	0.84	0.08	0.69 to 0.99	<0.0001	≥90 dBA	0.53	0.07	0.41 to 0.66	<0.0001
<95 dBA/>6 years	0.54	0.03	0.48 to 0.60	<0.0001					
≥95 dBA/>6 years	0.43	0.13	0.18 to 0.69	0.0008					
Better worker training	−0.04	0.03	−0.10 to 0.02	0.1534	Better worker training	−0.05	0.06	−0.18 to 0.07	0.4015

information. This limitation should be substantially reduced by improved record keeping and audiometric testing in recent years.

A novel metric for calculating historical cumulative noise exposures, duration of exposure within stratified noise intensity levels, was also evaluated and proved to be more useful in predicting NIHL than L_{eq}. One explanation is that using equal intensity exposures/time conversions across a wide range of noise intensities may not be appropriate. Animal models have shown that the adequacy of the exchange rate is dependent on both noise intensity and noise kurtosis,[21 22] and that the accuracy of L_{eq} predictions of NIHL risk is dependent on duration (hours per day), intensity and type (continuous vs intermittent) of noise exposure.[23–25]

Another explanation is that historical estimates of noise intensity for each subject, based upon limited sampling and extrapolation over time and job, may be too inaccurate to reliably equate a difference of 3 dBA with a doubling of exposure time. Exposure durations, which are usually based upon historical employment records, are generally far more accurate. It would be useful for future studies of NIHL to explore several ways of calculating cumulative noise exposures.

The use of bilateral hearing thresholds at 3, 4 and 6 kHz to evaluate NIHL proved to be a sensitive measure. Furthermore, the separate analysis for male and female workers demonstrated similar trends, but with substantive differences. This reflects the likelihood that there were gender differences in occupational noise distributions and compliance with HPD use,[26 27] in hearing loss profiles[28] and test variability,[29] as well as in the observed distributions by plant within this cohort.

The use of HPDs (generally associated with active enforcement) within this study was associated with reduced NIHL, even though we were not able to assess how well the HPDs were fitted or placed. This finding is in agreement with other recent studies, and should contribute towards motivating HPD use, as a sense of self-efficacy is associated with use.[9 10]

While increased audiometric testing was associated with increased NIHL, focus groups reported that workers with greater seniority were less likely to wear hearing protection, raising the possibility that these workers may also be more reluctant to have their hearing tested. Participation in audiometric screening by those with the greatest hearing loss may have been low until the programs became more universally enforced (as demonstrated by reduced times between audiograms).

No conclusions could be drawn on the impact of noise monitoring as there was insufficient within-plant variation in the data to determine its effectiveness. Similarly, worker training programs, which barely existed in these plants, did not have sufficient variation to demonstrate associations with NIHL. These results do not necessarily indicate that components of HCP implementation other than HPD use are not important. Better data for defining the implementation of these HCP components are needed before a more complete understanding of their associations with NIHL can be obtained. Furthermore, some components of HCPs may be better studied using factory-wide NIHL levels rather than individual levels.

Our analyses controlled for the level of noise exposure, and thus could not evaluate the preferred method of hearing conservation — the control or elimination of noise at its source through engineering controls or substitution. However, this study confirms earlier observations that HPDs remain the focus of HCPs.[7–9]

The limitations of this study are those associated with many historical studies, including missing and sparse information, and changes in measurement quality over time. Nevertheless, this study demonstrated that estimates based upon these limited data could still demonstrate differences between HCP programs and help us understand what make HCPs more effective. We recommend that quality audiometric and noise monitoring data, along with accurate records on HCP administration, be regularly collected and maintained to monitor the progress of these programs.

Acknowledgements The authors wish to thank all of those who participated in study for their time, interest and cooperation.

Funding This study was fully paid for by the National Institute for Occupational Safety and Health.

Competing interests None.

Provenance and peer review Not commissioned; externally peer reviewed.

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