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Methods for evaluating temporal trends in noise exposure

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Abstract

Objective—Hearing conservation programs have been mandatory in many US industries since 1983. Since then, three program elements (audiometric testing, hearing protection, and training) have been the focus of much research. By comparison, little has been done on noise exposure evaluation.

Design and study sample—Utilizing a large dataset (>10,000 measurements over 20 years) from eight facilities operated by a multinational aluminum manufacturing company, we evaluated several approaches to assessing temporal trends in Time Weighted Average (TWA) exposures and the fraction of measurements exceeding 85 dBA by facility, by exposure group within facility, and by individual worker within facility.

Results—Overall, exposures declined across locations over the study period. Several facilities demonstrated substantial reductions in exposure, and the results of mean noise levels and exceedance fractions generally showed good agreement. The results of analyses at the individual level diverged with analyses by facility and exposure group within facility, suggesting that individual-level analyses, while challenging, may provide important information not available from coarser levels of analysis.

Conclusions—Validated metrics are needed to allow for assessment of temporal trends in noise exposure. Such metrics will improve our ability to characterize, in a standardized manner, efforts to reduce noise-induced hearing loss.

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

Introduction

Occupational hearing loss is one of the most common occupational diseases in the US and other developed and developing nations (Sataloff & Sataloff, 1996). In an attempt to address this issue, the United States (US) Occupational Safety and Health Administration (OSHA) promulgated a regulation establishing a 90 dBA eight hour Time Weighted Average (TWA) Permissible Exposure Limit for occupational exposure to noise in 1972 (OSHA, 1971). This regulation was later recognized to be inadequately protective of worker health, so OSHA created an amendment requiring the establishment of hearing conservation programs (HCPs). The Hearing Conservation Amendment (HCA) went into effect in 1983 (OSHA, 1983), and established an 85 dBA TWA Action Level. TWA exposures >85 dBA are widely recognized as capable of causing noise-induced hearing loss (NIOSH, 1998).

Since the passage of these regulations, some aspects of occupational hearing conservation in the US have showed tremendous innovation and improvement. For example, the HCA requires audiometric surveillance for noise-exposed workers, and this is now routinely performed for millions of US workers. Ongoing collection of audiometric data has produced opportunities for early detection of noise induced hearing loss; to this end a number of calculations of audiometric “shifts” have been required by OSHA and additional techniques have been developed for audiometric data analysis (Rabinowitz et al, 2006; Rabinowitz et al, n.d.; Royster & Royster, 1986; Adera et al, 1993)Advances have also been made in worker and supervisor training (NIOSH, 1998; Trabeau et al, 2008). Hearing protection device (HPD) use has also seen dramatic changes in the past 30 years, with the implementation of HPD use audits, the development of new, increasingly sophisticated types of HPDs, and the advent and increasingly widespread adoption of individual fit-testing of HPD attenuation. Finally, advances have been made in noise control, with the development and marketing of quieter industrial and construction equipment, largely as a result of initiatives and requirements developed outside of the US, and particularly in the European Union.

One area of HCPs in which very little progress has been made is the assessment of occupational noise exposures, allowing employers to determine whether occupational noise is being successfully controlled, since such control is considered to be the most effective means of preventing noise induced hearing loss. To be sure, there have been innovations and substantial improvements in the capability of noise measurement equipment. For example, use of modern dosimeters capable of assessing multiple channels of noise simultaneously, of measuring noise levels underneath HPDs while they are being worn, and of notifying workers in real-time of exposure situations is now widespread. However, there has been virtually no work on a critical element of HCPs – the evaluation of trends in noise exposure among workers enrolled in HCPs to determine whether individual exposures are in fact decreasing.

While consensus methods have been accepted for the measurement of noise, for a variety of aspects of audiometric surveillance, and for testing of hearing protector attenuation achieved by workers, no consensus methods appear to exist for analysis of noise exposure trends. Even the recommendations for frequency of noise monitoring are ill-defined, with some agencies arguing for routine, scheduled monitoring (NIOSH, 1998) and others suggesting a need for monitoring only after major changes (OSHA, 1983). This is surprising, given the fact that noise assessments represent the foundation of any HCP; without such assessment, it is not possible to judge the adequacy of HPDs, to tailor worker training to the levels found in a particular facility, or to identify appropriate noise control measures. Some evidence even suggests that frequent monitoring of noise exposures, with regular feedback to workers about their own exposure levels, may result in altered worker behaviors (Michael et al, 2011) and even reductions in noise exposure (McTague et al, 2013).

In both historical and contemporary occupational health settings, the success of HCPs has typically been judged through evaluation of audiometric surveillance results or qualitative measures, e.g., input from focus groups (Prince et al, 2004). There are many examples of studies which have examined audiometric results in an attempt to determine the effectiveness of HCPs, including studies of longitudinal data across one (Savell & Toothman, 1987; Brink et al, 2002) or multiple (Lee-Feldstein, 1993; Dement et al, 2005) facilities within the same industry or military occupations (Wolgemuth et al, 1995; Muhr & Rosenhall, 2011)Several studies that have utilized audiometric results to analyze HCP effectiveness have found that audiometric test results do not align well with categorized noise exposures (e.g., “high” vs “low”) (Bohnker et al, 2002). Only a few studies have also evaluated quantitative noise exposures with regards to HCP performance (Savell & Toothman, 1987; Lee-Feldstein, 1993; Davies et al, 2008), and some have determined that categorized exposures are more useful than continuous quantitative estimates (Heyer et al, 2011). Some studies have also suggested that ANSI guidance on HCP analysis using audiometric test results is not useful (Simpson et al, 1998; Adera et al, 1993)

Together these findings suggest a need for new approaches to evaluate the performance of HCPs in terms of success at controlling noise. Unfortunately, most HCPs utilize lagging indicators of program performance, such as trends in audiometric test results, and will therefore always be reactive in nature. By the time a trend in hearing loss is identified, irreversible damage to workers’ hearing has already occurred. Routine, ongoing noise exposure assessments and trend analyses offer a potential leading indicator of program performance. Intuitively, if occupational noise levels are being reduced over time, the risk of occupational noise-induced hearing loss is also reduced to some degree. However, without standardized tools for assessment of noise exposure trends, analyses of such trends will remain limited – and in many HCPs, noise measurements appear to be partially or completely disconnected from audiometric program elements (Biggs & Everest, 2011; Pelausa et al, 1995).

Given the paucity of information available on this topic, and the importance of noise assessment and control in HCP effectiveness, standardized statistical approaches to evaluate noise trends are needed. In defining such approaches, three aspects must be considered: the amount of noise measurement data available; the metric of choice; and the level of analysis. Limited or sparse noise measurement data complicate the evaluation of trends in noise exposures, and may require application of Bayesian approaches, which are beyond the scope of this paper. A robust dataset of noise measurements creates opportunities for a wide range of analytical approaches. The metric of choice must also be determined. With noise, two metrics are commonly used: the mean noise level, typically computed across TWA measurements, or an exceedance fraction (e.g., the percentage of measurements which exceed a specified noise level, often 85 dBA). The level of analysis is also an important issue. For example, some authors have suggested that individual-level assessments represent the gold standard for occupational exposure assessment (Nieuwenhuijsen et al, 2006), while others have actively argued against an individual approach (Royster et al, 2003), or suggested that group-level assessments were more desirable (Tielemans et al, 1998). If a group-based approach is adopted, at what level should groups be developed? Grouping strategies may focus on different facilities (e.g., a facility-level analysis), or on the creation of Similar Exposure Groups (SEGS) (Bullock & Ignacio, 2006) based on some shared determinant of exposure. A few studies have explored different strategies for examining facility- or site-level exposures (Neitzel et al, 2011c; Davies et al, 2009)group-based exposures (Neitzel et al, 2011a; Davies et al, 2008), and individual-level exposures (Neitzel et al, 2011b) to noise, and very few have done so longitudinally in order to look for trends (Neitzel et al, 2011b). The results of these studies have been variable, which suggests that these approaches may yield differing, and potentially conflicting, conclusions regarding trends in noise exposure.

The goal of this study was to use a large existing industrial noise exposure dataset to develop and evaluate several novel metrics for use in evaluating the effectiveness of hearing loss prevention programs. Workers exposed to high noise at facilities operated by the participating company are enrolled in the company’s comprehensive HCP, which predates OSHA’s HCA. As part of this program, individual facilities are required to take a number of steps to protect workers’ hearing, including noise exposure assessment, noise control efforts, baseline and annual audiometric testing for workers in the program, worker training, and use of hearing protectors. Company locations are encouraged to assess and control noise exposures. However, an analysis of noise exposure trends involving multiple facilities had not been conducted.

Methods

This study was conducted using a large administrative dataset of noise exposures associated with work in the aluminum industry. The dataset included measurements made between 1992 and 2011 at eight different facilities operated by the participating company, which ranged from medium sized (~500 employees) to large (>1500 employees) (Table 1). The facilities are involved in a variety of operations, including smelting, ingot production, forging, and sheet rolling, and workers at each facility perform a wide range of jobs related to the production of aluminum and manufacture of aluminum products. These facilities were selected because they had complete noise measurement data available for the entire study period, and because employment records at the facilities allowed workers in given job titles to be collapsed into standardized exposure classifications.

All data used for this study were made available as the result of a partnership between the participating company, Stanford University, and Yale University that was developed with the goal of identifying and implementing occupational safety and health policies for the company. These ongoing studies have been reviewed by the human subjects committees for both institutions. Analyses were conducted using SAS 9.3 (SAS Institute, Cary, NC); results were considered significant where $p<0.05$.

Data sources—The company maintains a number of computerized databases to facilitate its US operations. While these databases are unique in both purpose and design, development of a system of encrypted unique identifiers has enabled the company, working with a research team from Yale University School of Medicine, to link the datasets. This allowed for the linkage of the human resources (HR) database containing job history data for each employee to noise measurements contained in the company's industrial hygiene (IH) database. Additional details on each of these databases are provided below.

HR database: The HR database was used to construct job histories from 1992 to 2011 for each hourly worker at the eight study plants. This database, described in detail elsewhere (Pollack et al, 2007; Taiwo et al, 2009), contains complete demographic and job history information for each employee.

Industrial hygiene database: Noise exposure data were obtained from the company's industrial hygiene (IH) database. Thecompany requires routine random personal noise measurements for all jobs with exposures that potentially equal or exceed an 8-hour TWA of 82 dBA, and workers must be enrolled in the company HLPP in areas where at least 5% of the noise measurement samples equal or exceed this level. These personal measurements are used to estimate an average noise exposure level for each job. Note that the company's voluntary 82 dBA TWA occupational exposure limit is more protective than the mandatory 85 dBA Action Level for hearing conservation established by the Occupational Safety and Health Administration (OSHA)

Metrics and data analysis—Our analysis included hourly employees at the eight locations who had job titles we were able to link to a standardized code, described in detail below. We developed and evaluated a number of metrics, including metrics designed to assess the degree of noise exposure assessment activity at each facility, as a surrogate for resources dedicated to the facility's HLPP; and metrics designed to assess changes in noise levels over time at the level of facility, for SCs within facility, and for individual workers within facility. Each of these metrics is described below.

We evaluated the average number of noise measurements per year over the study period, and normalized this to a rate per 100 employees. This normalization allows for a more fair comparison of noise measurement efforts across facilities with differing numbers of employees. Use of an average number of measurements, rather than a rate, could make measurement efforts at smaller facilities appear inadequate compared to larger facilities where more measurements are needed to accurately characterize exposures in a larger and more diverse workforce. This metric was intended to provide a crude evaluation of the resources each facility dedicated to noise exposure assessment, which may be an indicator of overall resources dedicated towards the facility's HLPP over the entire study period. To evaluate more recent efforts regarding noise exposure assessment, we computed the average number of measurement per year over the three-year period 2009-2011 for each location, and also the ratio of the normalized rate of measurements in these final three years to the overall study period (as a measure of intensity of recent measurement activity).

To assess noise levels at the facility level, we calculated the mean TWA noise levels across all measurements made in the first (1992-1994) and last (2009-2011) three years of our study period for each location. We also calculated the percent of noise measurements that exceeded 85 dBA (i.e., exceedance fractions) during these two periods. We then computed annualized rates of change for both mean noise exposure (dBA/year) and percent of measurements exceeding 85 dBA (%/year) by fitting a simple linear regression line which incorporated annual average levels across the entire study period (1992 -2011 using the mean noise exposures and percentage of noise exposures over 85 dBA, respectively.

By use of a process described elsewhere (Pollack et al, 2007), job titles in the company IH database were collapsed into standardized codes (SCs) to enable linkage of exposure information collected by job title to individual workers. SCs were created by company personnel by identifying different job titles which conduct essentially identical work tasks and aggregating these job titles under a single standardized name (e.g., an SC); they can be considered to be analogous to SEGs. SCs were created based on work tasks to simplify exposure assessments, and were not created specifically to evaluate noise. Occupational noise exposure levels for each SC for the study period of 1992 to 2011 were created by assigning the arithmetic mean of all full shift personal noise measurements available within that period for all jobs within that SC. Workers in jobs for which no noise measurements were available (about 10% of jobs) were excluded from this analysis. For workers who changed SCs within a given study year, we weighted the assigned noise exposure assignment by person-months contributed to each SC during that year.

To assess noise levels at the SC level, we calculated mean SC TWA noise levels for the first (1992-1994) and last (2009-2011) three years of our study period for each location. We also determined the percent % of SCs with an average noise exposure > 85 dBA for the same periods for each location. Annualized rates of change in SC for mean noise exposure (dBA / year) and % SCs with an average noise exposure >85 dBA were then calculated by fitting a simple linear regression line across all annual values with these metrics from 1992-2011. SCs with fewer than 3 noise measurements were not used in these calculations, and regressions were weighted by the number of SCs in each year.

We evaluated noise levels for individual workers by assigning SCs and corresponding average noise exposure levels to each job a worker had over the entire study period. The average noise exposure was calculated for the first (1992-1994) and last (2009-2011) three years of our study period for each location. The annualized rate of change in noise exposure (dBA/year) was then calculated for each worker by fitting a simple linear regression line through all of their individual-level annual noise exposures over time. The average slope of these individual exposure level changes over time was then calculated for each location. As a sensitivity analysis, we repeated this analysis after adding in employees in a job with no noise exposure measured, and assigning these jobs an exposure level of 65 dBA, a level which approaches by does not exceed 70 dBA, the level at which no hearing loss is expected regardless of duration of exposure (EPA, 1974) We conducted this sensitivity analysis to evaluate the potential importance of low-level noise exposures among employees otherwise excluded from our analyses.

Results

The facilities included in the study employed 12,534 hourly workers over the study period from 1992-2011 who received at least two audiograms, had audiometric data at least every other year during their employment, and worked in noisy jobs (Table 1). Approximately 59% of workers in the study came from three of the eight facilities (numbers 1, 3, and 7). All facilities had stable or increasing employment over the study period.

The eight study facilities collected a total of 10,782 full-shift TWA noise measurements over the entire study period (Table 2). Facilities 1 and 5 had high measurement rates. Facility 4 had the second-lowest rate of measurements at baseline, but showed a tremendous increase in measurement activity in the last three years of the study period, when it made 72% of its total measurements. The overall rate of measurements per 100 employees was slightly higher in the final three years (7.0 per year per 100 employees) than over the entire study period (6.4 per year per 100 employees). Facility size did not appear to be a significant factor in measurement effort over the entire study period.

Measured noise levels and exceedance fractions are presented in Table 3 at the level of facility. The range of mean TWA noise levels at baseline by facility was nearly two times greater in the final period than the baseline period. Facility 2 had the highest mean TWA levels and exceedance fractions in the baseline and final periods. Four of eight facilities in the baseline period had mean TWA levels >85 dBA, while only one facility (number 2) had a mean TWA level >85 dBA in the final period. Noise levels and exceedance fractions were reduced over the study period for all facilities except 3. Facility 6 showed the greatest annualized reduction in mean noise levels (−0.79 dBA/year), and facility 7 showed the greatest annualized reduction in exceedance fraction (−3.35%/year). Five of eight coefficients for annualized change in noise levels, and four of eight for annualized change in exceedance fractions, reached statistical significance ($p<0.05$).

Table 4 presents the noise levels at the SC level within facility. With one exception (location 5), the number of SCs within each facility remained stable or increased over the study period. Mean noise levels at baseline again varied among the study facilities, and the range of levels was again nearly twofold larger in the final period than the baseline period. The changes in mean noise levels and in exceedance fractions at the SC level indicated a general reduction in noise levels among exposure groups within these facilities. Facility 2 again had the highest mean noise levels and exceedance fractions by SC within facility in the baseline and final periods. Facility 6 showed the largest reduction in mean noise levels and exceedance fraction over time. Only one facility (3) showed an increase in mean noise levels and exceedance fraction over the study period at the SC level. Five negative slope coefficients for annualized changes in noise levels, and five for annualized changes in exceedance fractions, achieved statistical significance.

Noise exposures analyzed at the individual level showed generally consistent results (Table 5). Facility 5 had the largest decreases in mean noise levels by individual within facility. Average rates of change in noise exposure at the individual worker level were negative for six out of eight facilities. The facilities which showed increasing noise levels at the level of individual within facility (4 and 8) were different from the facility identified as having increasing noise trends at the facility level (Table 3) and SC within facility (Table 4).

As a sensitivity analysis, we repeated the above analyses after adding in individuals who were enrolled in HCPs at the study facilities but who did not have assigned noise exposures. These individuals were assigned exposures of 65 dBA for this purpose of this secondary analysis. The results of this analysis (data not shown) did not differ substantially from those of our primary analyses, suggesting that exclusion of presumably non-noise exposed individuals from this HCP analysis did not influence our findings.

Discussion

This study presents the results of a large-scale, multi-metric analysis of noise measurements made to support HCPs at eight different facilities operated by a single multinational aluminum manufacturing company. The metrics used in the study – mean TWA noise level and percent of TWA noise measurements >85 dBA – combined with analyses conducted at the facility level, at the level of SC within facility, and at the level of individual within facility, represent one of the few temporal analyses of noise measurement data in the published literature.

The majority of facilities showed decreasing noise levels over time. However, there are some discrepancies between the results of analyses at the various levels. Facility 3 showed increased noise levels and increased exceedance fractions at the facility and SC within facility levels, but showed reductions in noise levels and exceedance fractions at the individual within facility level. Facilities 4 and 8 demonstrated reductions in noise levels and exceedance fractions at the facility and SC within facility levels, but demonstrated increases in noise exposure at the individual within facility level.

While the two exposure metrics assessed here (noise levels and exceedance fractions) generally show good agreement, there is incomplete convergence of trends evaluated at the facility level and the SC within facility and individual within facility levels. The fact that trends at the facility and SC within facility levels were generally consistent suggests that analyses at the level of facility and SC within facility yield similar results. If this is the case, facility-level assessment would be preferable for simplicity and ease of analysis. Facilities with the highest noise levels generally had the greatest reductions in noise, but even with these reductions exposures at these facilities may have remained high enough to produce noise-induced hearing loss. One key difference between the individual within facility level of analysis and analysis at the facility and SC within facility level is that in the individual-level analysis, changes in noise levels are computed after noise levels are assigned to individual workers, whereas in the facility and SC within facility analyses changes in noise levels are computed without consideration of individual workers. If the measurements made in various areas of the participating facilities were collected in a way that was biased in comparison to individuals' true exposures – for example, if noise levels assigned to an SC consistently over- or under-estimated the exposures of individual members of that SC, or if certain exposures occurring within an SC were assessed in a manner that was disproportionate to the number of workers within that SC that received that exposure (i.e., oversampled), different results would be expected for an individual-level analysis (as we see here) compared to facility and SC within facility level analyses. At an individual worker level, the magnitude and effects of bias in exposure assignment or effects of disproportionate exposure sampling are difficult to assess. However, the potential existence of such bias cannot be discounted. This highlights the need for worker and area sampling techniques used to establish exposures for SCs to be representative of workers' actual exposures and activities. Random sampling, which is extensively employed by the company, is one way to increase the likelihood that exposure data are representative, and increases our confidence that the differences between facility-level and individual-level analyses are real. The differences between the individual and other levels of analyses presented here suggests that individual-level analyses, while complicated, have merit and may provide insights into exposure that the facility and group-level analyses cannot.

Despite similarities in management structure that would be expected among facilities operated by the same company, substantial differences were noted in the intensity of the noise measurement effort at the study facilities. These differences did not appear to be related to the number of workers employed at the facilities, but may be related at least in part to the type of operation at each facility. Generally, the facilities that collected the most noise measurements featured smelting and sheet mill operations. These operations are among the noisiest in aluminum manufacturing. It is notable that, at baseline, four of eight facilities (Table 3) had mean TWA noise levels at or above 85 dBA, while during the final three years of the study only one did, and that substantial reductions in exceedance fractions were also seen at five of eight facilities over the course of the study. While these reductions may have resulted from a variety of circumstances – for example, noise control efforts or economic and production changes – regardless of the reason, this trend nevertheless demonstrates that reduction of noise levels over time is feasible.

There are few studies to which our evaluation of temporal trends in noise exposure can be compared. Neitzel et al (Neitzel et al, 2011b) evaluated over 1,000 TWA noise measurements made on construction workers in Washington state between 1998 and 2008 as part of a prospective study of noise-induced hearing loss. Only a single metric, TWA noise level, was assessed, all analyses were conducted at the level of the individual worker, and the only temporal evaluation conducted was a simple linear regression applied to TWA noise levels over time. The slope of the regression line was not significantly different from zero, leading the authors to conclude that noise levels in the construction industry did not increase or decrease substantially over the 10-year study period. A previous study of employees of the same aluminum manufacturing company assessed here examined temporal variations in noise exposures of 418 different jobs, and found significant trends in only 33 (Rabinowitz et al, 2007). Middendorf (Middendorf, 2004) conducted an analysis of more than 150,000 compliance measurements made by OSHA between 1979 and 1999 as part of routine inspections of and consultations with manufacturing facilities and other workplace types. Linear regression analyses indicated an overall decline in both number of measurements and measured noise levels over the study period. Manufacturing noise levels measured according to the OSHA AL decreased by about 0.2 dBA/year between 1979 and 1999. Noise levels were also found to increase by 0.3 dBA with every increase of 100 in facility employment. Similar changes were seen in the service industry. The limitation of this analysis of OSHA data is the source of data itself – OSHA measurements are often made to represent “worst case” scenarios, so the data analyzed likely represent only the upper end of the exposure distribution, unlike the current dataset, which better reflects the full range of exposure conditions.

The intensity of the noise measurement effort at the participating company was high overall. Across all facilities, on average nearly 8% of the workforce completed full-shift noise measurements each year. By comparison, Daniell et al (Daniell et al, 2006) found that the majority of companies in eight different industries in Washington state reported making noise measurements as part of their HCP, but that most companies did not keep good records of these measurements or analyze trends or patterns in the measured noise levels. The large number of full-shift TWA measurements made at most plants over the study period compares favorably to other studies of HCPs (Lee-Feldstein, 1993; Brink et al, 2002; Davies et al, 2009) and the fact that the high rate of measurements was sustained by many of the study facilities across the entire study period is an indication of an active approach to noise exposure assessment at the corporate level.

Limitations

Despite the large dataset available for analysis, this study had several limitations. The most important limitation is the lack of detailed individual-level information regarding use of hearing protection devices by the workers assessed in the study. There is undoubtedly measurement error and misclassification in the noise exposure estimates assigned to the facilities, SCs within facilities, and individuals within facilities that were evaluated in this study. However, it is likely that this measurement error is quite small compared to the error introduced through our inability to adjust for exposure reductions resulting from hearing protection use. The proper use of hearing protection can result in 30 dB or more reductions in noise exposures measured through conventional dosimetry (Berger, 2000), while incorrect use of hearing protection can result in attenuation of only a few dB (Neitzel & Seixas, 2005), and non-use of hearing protection results in zero attenuation. Use of hearing protection among workers employed by the participating company is generally high; however, it is possible that there was differential use among workers at different facilities, and attenuation achieved by an individual user of hearing protection can also vary over time. Previous studies of this workforce have suggested that use of hearing protection may be higher in high noise environments (Rabinowitz et al, 2007). Uncertainties with regard to hearing protection use could be addressed through individual-level correction for hearing protection use. Unfortunately, however, such data were not available for use in this study.

An additional factor that limits our ability to draw inferences about trends in noise exposure at the study facilities is our lack of detailed knowledge about conditions and circumstances at these facilities over the study period. For example, no information was available about a number of potential factors that could influence noise measurement efforts at the facilities, such as changes in management or occupational health and medical personnel, recordable hearing losses, hearing loss claims, inspections by compliance officers or corporate auditors, labor-management relations, etc. In addition to possible variations in local conditions, the aluminum manufacturing industry also experienced economic swings over the study period, which resulted in fluctuations in employment and production. These swings may have substantially influenced noise levels at the participating facilities in a way that was completely independent of the HCPs operated by each facility. Some of the facilities may also have implemented noise controls during the study period and reduced the need for an ongoing measurement campaign. This would be a desirable outcome, yet such plants would then appear to have a reduced measurement intensity.

Conclusions

The results of our study suggest that a focus on changes in measured noise levels, rather than changes in exceedance fractions, may yield more robust results. Facility-level analyses are the simplest approach to temporal evaluations, and produced results that were generally consistent with analyses conducted at the level of SC within facility, which represents a more challenging and complicated analysis. Individual-level analyses, while much more complicated to execute, provide additional useful information about HCP performance. Differing results between the individual-level and facility- or SC within facility-level analyses may be a useful indicator of problematic noise measurement approaches, such as oversampling areas where few workers are employed or potential biases in exposure levels assigned to SCs. None of these approaches should be interpreted as a proven method; rather, these and other approaches need to be evaluated in a number of different industries, and should also be assessed for different types of noise exposure. Many exposures in aluminum manufacturing are relatively constant, which is a very different temporal pattern than what might be experienced in, for example, the construction or service industries.

Current use of audiometric test data as a lagging indicator of noise levels is a reactive approach and can never result in the proactive correction of overexposures to noise. Nevertheless, this is the approach that most HCPs take – if they conduct any temporal analysis at all. This study highlights the importance and need for leading indicator metrics that can evaluate the performance of HCPs prior to the occurrence of irreversible noise-induced hearing loss. Further development of methods and metrics for temporal evaluation of noise levels at both the individual- and facility-level is needed and can help address this common HCP deficiency.

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Table 1

Descriptive statistics for employment and hearing loss

Location	Location operations	Years	N hourly employees		
			1992	2011	Total
Overall	--	1992-2011	4883	6468	12534
1	Smelter, aluminum ingot plant, can reclamation, hot and cold rolling mills for aluminum sheet, power plant	1992-2011	858	834	2083
2	Aluminum forge	1992-2011	377	695	1294
3	Aluminum sheet and plate mills	1992-2011	816	1543	2624
4	Aluminum extrusion	1992-2011	468	584	1109
5	Smelter, aluminum ingot plant, aluminum extrusion	1992-2011	529	571	1192
6	Aluminum refinery	1992-2011	316	449	962
7	Smelter, aluminum ingot plant, hot and cold rolling mills for aluminum sheet	1992-2011	1221	1490	2669
8	Smelter, aluminum ingot plant, powdered aluminum production	1992-2011	298	302	601

Table 2

Noise measurements

	Entire study period (1992-2011)				Final 3 years (2009-2011)				Final / entire study period
Location	N meas.	Mean n meas./ year	Mean n employees	Mean n meas./ year per 100 employees	N meas.	Mean n meas./ year	Mean n employees	Mean n meas./ year per 100 employees	Ratio of normalized rates
Total	10,782	539	8,441	6.4	1,499	500	7,158	7.0	1.1
1	2,174	109	1,204	9.0	238	79	1,096	7.2	0.8
2	1,248	62	991	6.3	247	82	781	10.5	1.7
3	2,273	114	1,805	6.3	193	64	1,681	3.8	0.6
4	765	38	777	4.9	554	185	642	28.8	5.9
5	1,273	64	844	7.5	190	63	616	10.3	1.4
6	516	26	593	4.4	80	27	466	5.7	1.3
7	1,888	94	1,804	5.2	171	57	1,562	3.6	0.7
8	645	32	422	7.6	238	79	1,096	7.2	0.9

Table 3

Noise exposures at facility level

	TWA noise levels (dBA)						Measurements > 85 dBA			
	Baseline (1992-1994)		Final (2009-2011)		Δ Baseline-final		Baseline (1992-1994)	Final (2009-2011)	Δ Baseline-final	
Location	**N**	**Mean**	**N**	**Mean**	**dBA/yr**	**p-value**	**N (%) >85 dBA**	**N (%) >85 dBA**	**%> 85 dBA/yr**	**p-value**
1	421	81.5	238	80.6	−0.10	0.02	82 (19.5)	50 (21.0)	−0.21	0.51
2	147	87.1	247	85.9	−0.18	0.26	102 (69.4)	171 (69.2)	−1.23	0.33
3	375	83.8	193	84.4	0.03	0.61	151 (40.3)	87 (45.1)	0.21	0.68
4	119	84.1	554	81.3	−0.12	0.44	51 (42.9)	136 (24.6)	0.20	0.90
5	239	85.0	190	79.7	−0.28	0.001	121 (50.6)	36 (19.0)	−1.52	0.03
6	115	86.9	80	74.3	−0.79	0.001	63 (54.8)	4 (5.0)	−2.32	0.01
7	101	86.5	171	79.6	−0.46	0.0000	66 (65.4)	27 (15.8)	−3.35	0.0000
8	95	83.5	64	76.7	−0.50	0.01	41 (43.2)	6 (9.4)	−1.70	0.01

Table 4

Noise exposures at SC level within facility

	N SCs		TWA noise levels						Measurements >85 dBA					
			Baseline (1992-1994)		Final (2009-2011)		Δ Baseline-final		Baseline (1992-1994)		Final (2009-2011)		Δ Baseline-final	
Location	Baseline (1992-1994)	Final (2009-2011)	N[*]	Mean (dBA)	N[*]	Mean (dBA)	dBA/yr [**]	p-value	N[*]	N (%) >85 dBA	N[*]	N (%) >85 dBA	> 85 dBA (% per yr) [**]	p-value
1	19	23	411	81.6	237	80.6	−0.11	0.01	19	2 (10.5)	23	3 (13.0)	−0.14	0.79
2	10	13	146	87.1	247	85.9	−0.18	0.26	10	7 (70.0)	13	9 (69.2)	−1.41	0.22
3	14	14	370	83.8	193	84.4	0.04	0.59	14	4 (28.6)	14	7 (50.0)	1.58	0.03
4	13	23	108	84.4	540	81.2	−0.14	0.35	13	5 (38.5)	23	1 (4.4)	−2.18	0.08
5	20	15	209	85.1	161	79.5	−0.31	0.0003	20	11 (55.0)	15	1 (6.7)	−2.95	0.0001
6	7	8	108	86.9	77	74.5	−0.84	0.002	7	4 (57.1)	8	0 (0)	−3.21	0.01
7	11	19	96	86.7	171	79.6	−0.45	0.00	11	7 (63.6)	19	1 (5.3)	−2.65	0.0005
8	8	8	93	83.7	61	76.9	−0.53	0.01	8	2 (25.0)	8	0 (0)	−2.13	0.02

[*] Required at least 3 measurements to be included

[**] Weighted by number of SCs in the year

Table 5

Noise exposures for individuals within facility

	Baseline (1992)		**Final (2011)**		**Δ Baseline-final, including each annual individual-level exposure**	
Location	**N workers**	**Mean TWA noise level (dBA)**	**N workers**	**Mean TWA noise level (dBA)**	**N workers**	**dBA/year**
1	614	80.3	521	80.0	2083	−0.14
2	197	86.1	399	86.5	1294	−0.07
3	488	83.6	851	83.3	2624	−0.05
4	238	82.4	224	83.0	1109	0.05
5	186	83.5	229	82.0	1192	−0.17
6	132	81.4	174	80.9	962	−0.14
7	685	81.8	1056	81.0	2669	−0.12
8	121	81.4	177	81.8	601	0.14