Ann. Occup. Hyg., 2016, Vol. 60, No. 5, 581–596
doi:10.1093/annhyg/mew001
Advance Access publication 17 February 2016

Comparison of Multiple Measures of Noise Exposure in Paper Mills

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Submitted 30 June 2015; revised 17 December 2015; revised version accepted 23 December 2015.

ABSTRACT

Background: Noise exposures are associated with a host of adverse health effects, yet these exposures remain inadequately characterized in many industrial operations, including paper mills. We assessed noise at four paper mills using three measures: (i) personal noise dosimetry, (ii) area noise measurements, and (iii) questionnaire items addressing several different aspects of perceived noise exposure.
Methods: We assessed exposures to noise characterized using the three measures and compared the relationships between them. We also estimated the validity of each of the three measures using a novel application of the Method of Triads, which does not appear to have been used previously in the occupational health literature.
Results: We collected 209 valid dosimetry measurements and collected perceived noise exposure survey items from 170 workers, along with 100 area measurements. We identified exposures in excess of 85 dBA at all mills. The dosimetry and area noise measurements assigned to individual subjects generally showed good agreement, but for some operations within mill, large differences between the two measures were observed, and a substantial fraction of paired measures differed by >5 dB. Perceived noise exposures varied greatly between the mills, particularly for an item related to difficulty speaking in noise. One perceived noise exposure item related to difficulty hearing due to noise showed strong and significant correlations with both dosimetry and area measurements. The Method of Triads analysis showed that dosimetry measures had the highest estimated validity coefficient (0.70), and that the best performing perceived exposure measure had validity that exceeded that of area measurements (0.48 versus 0.40, respectively).
Conclusions: Workers in Swedish pulp mills have the potential for exposures to high levels of noise. Our results suggest that, while dosimetry remains the preferred approach to exposure assessment, perceived noise exposures can be used to evaluate potential exposures to noise in epidemiological studies.

KEYWORDS: area measurements; dosimetry; job exposure matrix; method of triads; noise; perceived exposure

INTRODUCTION

Noise is one of the most common occupational exposures in developed and developing countries around the world. The most well-understood health effect of excessive noise exposure, noise-induced hearing loss (NIHL), was recognized hundreds of years ago, but unfortunately remains one of the most common occupational diseases globally (Sataloff and Sataloff, 1996; Nelson *et al.*, 2005). In addition to NIHL, a host of other health effects—including performance degradation, annoyance, cardiovascular disease, and injuries—are associated with occupational noise exposure (Basner *et al.*, 2014; Cantley *et al.*, 2015). Occupational regulations typically specify an unprotected 8-h time-weighted average (TWA) exposure limit of 85 A-weighted decibels (dBA) to protect workers' hearing ability (Arenas and Suter, 2014), although in most member states of the European Union the exposure limit value (mandated by Directive 2003/10/EC) is a TWA of 87 dBA that considers the attenuation of exposure achieved through mandatory use of hearing protectors by workers (European Union, 2003). The European Union directive also includes an upper exposure action value of 85 dBA, above which use of hearing protection, audiometric surveillance, implementation of noise controls, and worker training are required. The 87 and 85 dBA limits may not be sufficiently protective against non-auditory health effects like cardiovascular disease (de Souza *et al.*, 2015), and certainly do not protect all exposed workers from suffering any NIHL (NIOSH, 1998). To achieve complete protection against NIHL, a TWA or 75 or 80 dBA would be more appropriate (EPA, 1974; European Union, 2003), and indeed the European Union directive includes a lower exposure action value of 80 dBA TWA, above which hearing protection must be made available to workers, though use of the protection is not mandatory. There is some evidence that, despite knowledge of associated health effects and the existence of regulations, occupational noise exposures may in fact be increasing in some regions of the world (Eurofound, 2012).

Workers in many occupational settings, including manufacturing (Brueck *et al.*, 2013) and mining (Strauss *et al.*, 2014), have continuous exposures to high levels of noise, while workers in dynamic industries such as construction (Neitzel *et al.*, 2011b) and agriculture (Firth *et al.*, 2006) are exposed to highly variable noise levels. Exposures in complex occupational settings such as paper mills may be continuous or variable, depending on their activities, location, and nearby equipment (Toppila *et al.*, 2000).

There are three primary contemporary strategies for occupational noise exposure assessment codified in standard 9612.1-2009 published by the International Standards Organization: task-based, job-based, and full-day measurements (ISO, 2009). These three strategies refer to separate measurements made on each individual task conducted by workers, random measurements made throughout the performance of jobs, and measurements made over the duration of an entire working day, respectively. This standard provides recommendations for how to evaluate, select, and employ these three strategies for the purposes of occupational risk evaluation, and offers a useful guide for the development, implementation, and analysis of a new noise exposure measurement campaign.

While ISO 9612.1-2009 represents current exposure assessment best practices and provides a high degree of sophistication regarding the analysis of collected data, the recommended methods are not necessarily realistic and feasible for implementation by occupational health practitioners, and some of the nomenclature used in the standard (i.e. 'Homogenous exposure groups') is no longer commonly used in the occupational hygiene community (Ignacio and Bullock, 2006). Additionally, while ISO 9612.1-2009 provides extensive guidance on evaluating exposure profiles, identifying appropriate measurement instrumentation and techniques, and quantifying uncertainty, the strategies proposed in the standard do not align perfectly with traditional approaches to, and legacy data from, occupational noise exposure assessment in industry. For example, many industrial facilities have relied on a combination of two traditional approaches for occupational exposure assessment that have been fundamental to occupational hygiene (Nieuwenhuijsen, 2003) and occupational hearing conservation (Royster *et al.*, 2003) for decades. The first of these traditional approaches is short-term area measurements made with a sound level meter (SLM), which are location-based analogues of the task-based and job-based strategies advocated by ISO (2009), though, unlike many historical industrial noise measurements, ISO requires that such measurements be made at the position of the exposed workers' head. The primary advantages of area measurements, and reasons for their extensive use in industry, are their unobtrusive nature and the relative speed and ease with which they can be used to screen for high noise areas or equipment. Area measurements repeated at the same location over time can also be used to evaluate trends in facility noise levels. However, systematic and comprehensive area measurements are labor intensive and time-consuming, and may not be possible in some hazardous areas (Hager, 1998). Also, the degree to which measured levels represent individual workers' exposures has not been sufficiently evaluated (Shackleton and Piney, 1984).

Full-shift personal measurements using a noise dosimeter are the second traditional approach to noise exposure assessment. This approach is consistent with the full-day measurement strategy advocated by ISO (2009). Dosimeters integrate personal exposures from all of an individual's activities and locations over time, and therefore represent the gold standard for noise exposure assessment. However, collection of dosimetry data may: burden the measured worker; be unnecessarily complicated for fixed workstation, steady-state exposures (though it still yields usable and useful results if employed in this or any other exposure scenario); yield measured average exposures that are not generalizable to workers in other locations or involved in different activities, or even to different workshifts for the measured worker; and be especially susceptible to errors introduced through microphone position, measurement artifacts from microphone contact with clothing, and other issues (ISO 2009).

A third approach to noise exposure assessment that is not included in ISO 9612.1-2009 but that has been used in epidemiological studies is self-report, in which workers report their perceived exposures during specific tasks (Virji *et al.*, 2009) over periods of a workshift (Neitzel *et al.*, 2009) or longer (Neitzel *et al.*, 2011a). This approach offers several advantages, including low expense, logistical ease, and the ability to assess exposures during periods where the worker is inaccessible for direct measurements. Studies in specific industries have shown good agreement between measured and worker-reported noise levels (Ising *et al.*, 1997; Neitzel *et al.*, 2009), However, use of these measures introduces the possibility of substantial exposure misclassification (Schlaefer *et al.*, 2009) due to potential variability in individual perceptions, use of personal protective equipment, and other factors, so self-reported survey item performance must be validated against objective measurements of noise.

In situations where exposures have been assessed using multiple approaches, the opportunity arises to compare the performance of these approaches. Various statistical methods (e.g. limits of agreement, bias, precision, and accuracy, Cohen's κ, etc.) may be used to assess agreement between two measures (Neitzel *et al.*, 2011a), but options to assess three-way relationships—as would be needed for noise exposure where area, dosimetry, and self-reported measures are available—are limited. The Method of Triads (Kaaks and Riboli, 1997; Ocké and Kaaks, 1997) allows for estimation of the validity coefficient of each of the three measurements through a triangular comparison of two-way correlations between all three measures (Fig. 1). The Method of Triads assumes that errors for each measure are uncorrelated and

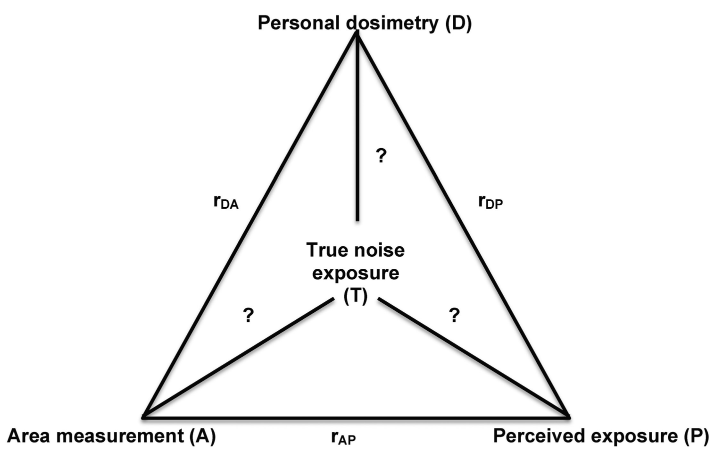


Figure 1 Conceptual diagram of the method of triads used to estimate the correlation between true noise exposure based on correlations (r) measured between noise dosimetry (D), area noise measurements (A), and perceived noise levels (P). Modified from Ocké and Kaaks (Ocké and Kaaks, 1997) and Kabagambe *et al.* (2001).

that each measure has a positive and linear relationship with the underlying (but unmeasurable) true exposure (Kaaks and Ferrari, 2006). This method has been utilized in a number of nutritional epidemiology studies (Kabagambe *et al.*, 2001; Shai *et al.*, 2005; Shuaibi *et al.*, 2008), but does not appear to have been used previously in the context of occupational exposure assessment.

The current study had three objectives. The first was to describe noise exposures in Swedish paper mills assessed via traditional area and dosimetry measurements, as well as worker self-report. These measurement approaches were selected in order to yield data consistent with historical exposure measurements at the participating mills, which will be presented elsewhere as part of a retrospective cohort epidemiological study (manuscript in preparation). The second was to estimate the validity of exposures assessed using each of these three approaches through a novel application of the Method of Triads. The third was to inform the exposure assessment approach for an ongoing retrospective cohort study of cardiovascular disease risk associated with noise, shift work, and paper dust exposures among 8683 Swedish soft tissue (e.g. household- and sanitary-paper, referred to as 'paper' hereafter) mill workers.

METHODS

Approval for the cohort study was obtained from the Regional Ethical Review Board in Gothenburg. All subjects received the results of the noise measurements made at their facility.

Site selection

Noise measurements and subject surveys were collected at four paper mills located in western and central Sweden between 2009 (mill 2) and 2013 (mills 1, 3, and 4). These mills were selected for measurement because they employ or employed workers participating in the retrospective cohort study. Each of the mills has been in service for >100 years and produced different kinds of paper, but all of them began producing soft paper between 1935 and 1947, and began producing soft paper exclusively between 1962 and 1982. Mill 1 had a capacity of 95 000 tons of paper products per year in 2000, produced on 3 paper machines by about 500 employees. Mill 2 had a capacity of about 75 000 tons year^{-1} in 2000, produced on 2 paper machines by about 200 employees. Mill 3 had a capacity of about 24 000 tons year^{-1} in 2000, produced on four paper machines. Finally, mill 4) had a capacity of about 22 000 tons year^{-1} in 2000, produced on three paper machines. Mills 3 and 4, historically operated by a single corporation, employed a total of about 190 workers in 2000. The feedstock for mills 1, 2, and 3 is 75–85% recycled paper, while mill 4 uses primarily fresh pulp.

Workers in each of the four mills are covered by the Swedish Work Authority occupational noise regulation AFS2005:16 (Arbetsmiljöverket, 2005). This regulation specifies a 8-h daily allowable exposure limit. $L_{EX,8h}$, of 85 dBA on average over an 8-h workshift. Workers exposed above this limit must use hearing protection devices (HPDs) that attenuate exposures to an $L_{EX,8h}$, of 85 dBA, and employers must consider and implement feasible administration or engineering controls to reduce $L_{EX,8h}$ exposures below 85 dBA. Note that the Swedish noise regulation is based on the European noise directive (Directive 2003/10/EC) (European Union, 2003), and differs only in setting a daily allowable exposure limit (accounting for the attenuation of hearing protection worn by workers) of 85 dBA $L_{EX,8h}$, as compared to 87 dBA for the European directive. In order to comply with the Swedish noise regulation, each of the mills had made area and/or dosimetry measurements in the past, and our exposure assessment effort was intended to complement these previous measurements.

Subject recruitment

Workers at each mill were approached by research staff during normal working hours and given a brief description of the study. Interested subjects provided implied consent by completing a brief survey, described below. Workers in a variety of job titles, work areas, and operations in each mill, as well as across different shifts within each mill, were approached to participate in a convenience sampling scheme. Workers on paper machines and converting machines were sampled at all four mills. Workers in pulp preparation areas, engineering workshops, and storage areas were sampled at mills 1, 3, and 4. At mill 1, workers were also sampled at a steam generation facility. Morning and night shifts were sampled at all four mills; at mills 1, 3, and 4, workers were also sampled on afternoon shifts, and at mills 3 and 4, workers were further sampled on day shifts.

Depending on their work area and work schedule, subjects had the potential to be approached to participate multiple times; in this event, they self-identified as previous participants and were not asked to complete additional surveys in order to reduce subject reporting burden. However, they were asked to wear a noise dosimeter in order to obtain more robust estimates of mean exposures by job title.

Area measurements

Area measurements were collected at all mills except mill 2. Measurements were made using a Type 2260 Investigator SLM (Brüel &Kjær, Nærum, Denmark) at locations measured by mill health and safety staff prior to the start of the current study. The SLM was calibrated at the start and end of each monitoring day. Measurements at each of multiple sampled locations in the three mills assessed were made for a duration of 60 s, yielding an equivalent continuous average exposure level over that period, $L_{pAEQ,60s}$. Measurements were made in areas where workers who were issued noise dosimeters (see section below) were stationed, and measurement locations were plotted on facility maps Data were entered into an Excel spreadsheet (Microsoft, Redmond, WA, USA).

Dosimetry measurements

Full-shift (i.e. 8 h) dosimetry measurements were made on workers at all four mills in job titles that had previously been sampled by mill health and safety staff. All measurements were made using Larson-Davis 705+ datalogging noise dosimeters (Larson-Davis, Depew, NY, USA) calibrated pre- and post-measurement and configured to workers' $L_{EX,8}$ exposures according to the Swedish occupational noise exposure regulation (i.e. A-weighting, FAST time constant, 3 dB time-intensity exchange rate, 85 dB criterion level, 8 hr criterion duration). Only two instrument settings were changed between mills: these were the measurement range (50–120 dB for mill 2, 60–130 dB for mills 1, 3, and 4) and the threshold (0 dB for mill 2, 80 dBA for mills 1, 3, and 4). These differences in settings between mills are unlikely to influence measured noise levels (Seixas *et al.*, 2001) in environments with noise levels that typically fall between 70 and 120 dBA, as was the case in the mills assessed.

Dosimeters were fit and removed from workers by research staff at the start and end of the shift, respectively. Microphones were located on the shoulder near the ear on the side of their dominant hand. Dosimeters were downloaded directly into a computer using Larson Davis Blaze software (Larson Davis, Depew, NY, USA), and $L_{EX,8}$ values were transferred into a Microsoft Excel (Microsoft, Redmond, WA, USA) spreadsheet.

Surveys

All subjects who wore dosimeters also completed a brief survey written in Swedish that contained items pertaining to workers' seniority, job title, shift, and several items related to perceived noise exposure. The first of these perceived (P) items, hereafter referred to as 'P1, *Difficulty hearing*,' was 'Is the noise levels sometimes so loud that you have problems hearing what others say?' and had six possible response categories of 'Never/almost never', 'About 10% of the time', 'About 25% of the time', 'About 50% of the time', 'About 75% of the time', 'About 90% of the time'. The second item, hereafter referred to as 'P2, *Speaking difficulty*,' was 'To make yourself heard:' and had five possible response categories of: 'Can you speak with a normal voice?', 'Do you need to raise your voice somewhat?', 'Do you need to raise your voice powerfully?', 'Do you need to scream, to the maximum?', and 'Because of the noise level is it impossible/almost impossible to communicate?'. The third and final item, hereafter referred to as 'P3, *How often raise voice*,' was 'How often are you exposed to high noise levels (so high that you must raise your voice/scream in order to communicate at a distance of 1m)?', and had five possible response categories of 'Never/almost never', 'Less than half the time', 'About half the time', 'More than half the time', and 'Always/almost always.' Each of these items has been used previously in research in occupational settings (Neitzel *et al.*, 2009; Fredriksson *et al.*, 2015). Note that, although any perceived noise exposure item could potentially incorporate hearing ability, as well as noise exposure, previous research has suggested than hearing ability does not influence perceived noise exposures among workers elevated noise exposure levels (Neitzel *et al.*, 2009). Worker survey data were entered into a Microsoft Excel (Microsoft, Redmond, WA, USA) spreadsheet for analysis.

Analysis

Data from the various spreadsheets were consolidated into a single file and exported into Intercooled Stata 12.1 (Stata Corp, College Station, TX, USA) for analysis. $P < 0.05$ were considered significant for all statistical tests. To allow for assessment of different strategies for grouping areas measurement data, area measurements at each mill were matched to individual workers in multiple ways, including by workers' locations, job titles, and operations.

To achieve our first objective, a description of exposures in the four mills, we computed descriptive statistics for dosimetry and area measurements overall and by mill, operation, location, and job title. We also assessed distributions of the categorical response from the P1, P2, and P3 perceived noise items from the survey. Differences in matched dosimetry and area noise levels overall and by mill, operation, and location were evaluated using Student's unpaired sample *t*-test. We also computed the bias in area noise level measurements compared to the matched dosimetry measurements, calculated as (dosimetry level, $L_{EX,8h}$) – (area noise level, $L_{pAeq,60s}$) and evaluated bias overall and by mill, operation, and location. The mean measured dosimetry and area noise levels associated with subjects' three perceived exposure item responses was determined, and Spearman correlations (ρ) were then computed to evaluate the associations between dosimetry ($L_{EX,8h}$) and area ($L_{pAeq,60s}$) noise levels and the response categories from each of the perceived noise items (P1, P2, and P3).

To achieve our second objective, which was to estimate the validity of each measurement method using the Method of Triads, we computed Validity Coefficients (VC) for each of the three exposure assessment methods using Equations 1–3:

$$VC_{area} = \sqrt{(r_{PA} \times r_{DA}) / r_{PD}} \quad (1)$$

$$VC_{Dosimetry} = \sqrt{r_{DA} \times r_{DP} / r_{PA}} \quad (2)$$

$$VC_{perceived} = \sqrt{r_{PA} \times r_{PD} / r_{DA}} \quad (3)$$

where P is the perceived noise item P_n demonstrating the highest ρ and most linear increase in dosimetry (D) and area noise levels by perceived exposure category, A is the area measurement strategy (by location, operation, or job title)with the smallest bias compared to the matched dosimetry level. Validity coefficients range from 0 to 1, with higher values indicating greater estimated validity. However, negative correlations between measures and high random variation can result in so-called Heywood Cases in which VCs are inestimable or invalid (i.e. greater than 1) (Ocké and Kaaks, 1997). A bootstrapping approach was used to estimate confidence intervals around the VCs for each method, as done previously by Kabagambe *et al.* (2001). In this approach, 1000 bootstrap samples of equal size (*n* = all valid cases of matched dosimetry, area noise level, and perceived noise measures, sampled with replacement) were obtained from the overall dataset. For each of these bootstrap samples, we computed VCs for dosimetry and area noise levels and perceived noise. We then computed as a non-parametric confidence interval for each of the three measures the 5th and 95th percentiles of the distribution of bootstrapped VCs using the Stata CI command, again following the methods used by Kabagambe *et al.* (2001).

RESULTS

A total of 170 subjects participated across the four mills (Table 1). Only one individual approached about the study refused to participate. Subjects averaged 19.5 ± 12.9 years of experience in paper mills. Over 42% of subjects came from mill 1, while only about 14% came from mill 3. These proportions are virtually identical to the employment distribution across the four mills, as well as the distribution of the retrospective cohort. Measurements were collected on workers in a range of job titles, with the largest categories being operator (27% of samples), paper machine operator (22%), and winding machine operator (12%).

To achieve the first objective of our study, describing the noise exposures associated with work in Swedish paper mills, 233 dosimetry ($L_{EX,8h}$) measurements were attempted, of which 209 (89.7%) were successful (Table 2). Unsuccessful measurements resulted from instrument failures, premature dosimeter removal by workers, and post-calibration failures. One hundred valid area measurements were collected. Thirty-nine of the 209 valid dosimetry measurements (18.6%) were repeated measurements on subjects; however, because repeated measurements on subjects were separated by a period of at least 3 months, we considered these repeated measurements to be independent of one another. Overall and for each mill and both types of noise measurement, the operation with the highest noise level and fraction of measurements >85 dBA was paper machine operation. Mill 3 had the highest overall dosimetry noise level and exceedance

Table 1. Demographic information on participating subjects ($N = 170$)

Variable	*n*	Mean	SD
Experience (years)	170	19.5	12.9
	n	%	
Facility	170	100	
Mill 1	73	42.9	
Mill 2	44	25.9	
Mill 3	23	13.5	
Mill 4	30	17.6	
Job title			
Operator			
General	46	27.1	
Core machine	14	8.2	
Paper machine	37	21.7	
Pulp	8	4.7	
Winding machine	21	12.4	
Electrician	5	2.9	
Mechanic	7	4.1	
Resource	12	7.1	
Truck driver	7	4.1	
Other	12	7.1	

fraction, while mill 4 had the highest area ($L_{pAEQ,60s}$) noise level and mill 3 the highest area noise level exceedance fraction. Dosimetry and area noise measurement results within mill often resulted in different rank ordering of operations by noise level. Statistically significant differences in dosimetry and area noise levels were noted overall and for converting operations, as well as for all measurements and converting measurements at mill 1, and converting measurements at mill 3. Dosimetry noise levels were significantly different between all mills and operations within mill, whereas area noise levels were not significantly different between mills, but were different between operations within mill 3. Variability for many operations (as summarized by the SD across measurements) exceeded the 3 dB measurement difference criteria proposed by ISO (2009). Note that the SDs in Table 2 represent the total error across the various sources of error described in ISO 9612.1-2009, i.e. variations in work, instrumentation and calibration, microphone position, measurement artifacts, and contributions from atypical noise sources or behaviors (ISO, 2009). Of these potential sources, variations in work and contributions from atypical sources are likely the major contributors to variability, as our sampling procedures minimized errors from the other sources.

Figure 2 shows the distributions of the responses to the three perceived noise items (P) completed by 170 subjects; results are presented by mill and overall. Differences were noted in the distribution of responses by mill for all three items. For P1, *Difficulty hearing*, subjects at only one mill (number 3) ever reported spending 90% of their time in noise levels that made it difficult to hear others. Interestingly, this mill also had the highest percentage of subjects who reported never or almost never spending time in noise. The largest P1 response category for all mills except mill 3 was about 10% of the time in noise levels that made it difficult to hear others. For P2, *Speaking difficulty*, there was substantial variability between mills. At two of the mills (2 and 4), no subjects ever reported noise levels high enough to require screaming to communicate or so high that communication was impossible. The dominant P2 response category for each mill was the need to raise the voice somewhat to be heard. The smallest variation among mills was noted for P3, *Raise voice*.

The estimates of bias in dosimetry ($L_{EX,8h}$) measurements as compared to area ($L_{pAeq,60s}$) measurements are displayed in Table 3. Overall, dosimetry measurements were 1.5 ± 5.5 dB higher than matched area measurements—well within the 2 dBA tolerance of a Type 2 noise measurement device (ANSI, 1996). Mean overall bias was smallest by location and largest by job title, but the bias in dosimetry measurements compared to area measurements showed a large range of 14.8 to −16.0 dBA overall, with only slightly more than 1/3 of area noise levels within 5 dBA of the matched personal noise levels. Mean bias was smallest at mill 1 and largest at mill 4, but varied substantially within mill. The scatterplot of area versus dosimetry noise levels by location within mill (Fig. 3, which also includes Spearman correlation coefficients) shows the relationship between the measures within each mill, as well as the approximate magnitude of bias (shown

Table 2. Results for noise dosimetry and area measurements overall, by mill, and by operation within mill

Facility/operation	Dosimetry time-weighted average ($L_{EX,8h}$ dBA)				Area average ($L_{pAEQ,60s}$), dBA)			
	n	Mean	SD	%>85	*n*	Mean	SD	%>85
Overall*	209[a]	85.1***	5.5	57.1	100	83.6	5.8	44.0
Converting*	112	84.1**	3.9	51.9	71	81.8	7.3	30.9
Papermaking	51	90.2**	4.5	88.2	25	88.4	9.5	80.0
Pulping	20	84.2**	4.6	43.4	4	86.0	3.5	50.0
Other	26	81.8**	8.0	55.6	—	—	—	—
Mill 1*	75	83.6	5.9	46.7	52	83.5	9.9	
Converting*	33	84.6**	3.6	48.4	44	82.7	8.9	27.5
Papermaking	16	88.9**	5.3	87.5	6	88.7	16.3	70.0
Pulping	11	82.3**	4.6	27.2	2	86.5	5.7	37.1
Other	15	80.1**	8.3	33.0	—	—	—	—
Mill 2	47	85.7	5.9	53.2	—	—	—	—
Converting	31	82.3**	3.1	45.7	—	—	—	—
Papermaking	16	92.4**	4.1	87.5	—	—	—	—
Pulping	—	—	—	—	—	—	—	—
Other	—	—	—	—	—	—	—	—
Mill 3	36	86.2	4.1	65.9	26	83.6	5.8	58.4
Converting*	16	85.3**	4.7	68.0	15	80.0$	4.1	57.4
Papermaking	13	88.5**	3.5	69.2	9	89.1$	4.0	96.4
Pulping	4	84.4**	0.8	50.0	2	85.5$	1.6	50.0
Other	3	84.4**	2.8	66.7	—	—	—	—
Mill 4	51	85.9	4.9	65.6	22	83.8	6.8	31.8
Converting	32	84.9**	4.1	61.9	12	80.7	1.7	0.0
Papermaking	6	91.7**	1.3	100.0	10	87.5	8.8	70.0
Pulping	5	88.3**	4.2	60.0	—	—	—	—
Other	4	84.9**	3.5	50.0	—	—	—	—

[a]37 subjects were monitored on 2 days, and 1 was monitored for 3 days.
*Difference between dosimeter and area dBA levels, *t*-test, $P < 0.05$.
**Difference between operations within location, ANOVA, $P < 0.05$.
***Difference between mills, ANOVA, $P < 0.05$.

by the deviation of the fitted line from the perfect agreement line), which was smallest at mill 3 and largest at mill 4. The pattern in mill 1 suggests systematic overestimation of measured area noise levels above 85 dBA compared to dosimetry levels, possibly due to monitored workers spending short periods of time in the noisiest measured areas, whereas the pattern in mill 4 suggests the opposite (i.e. workers spending

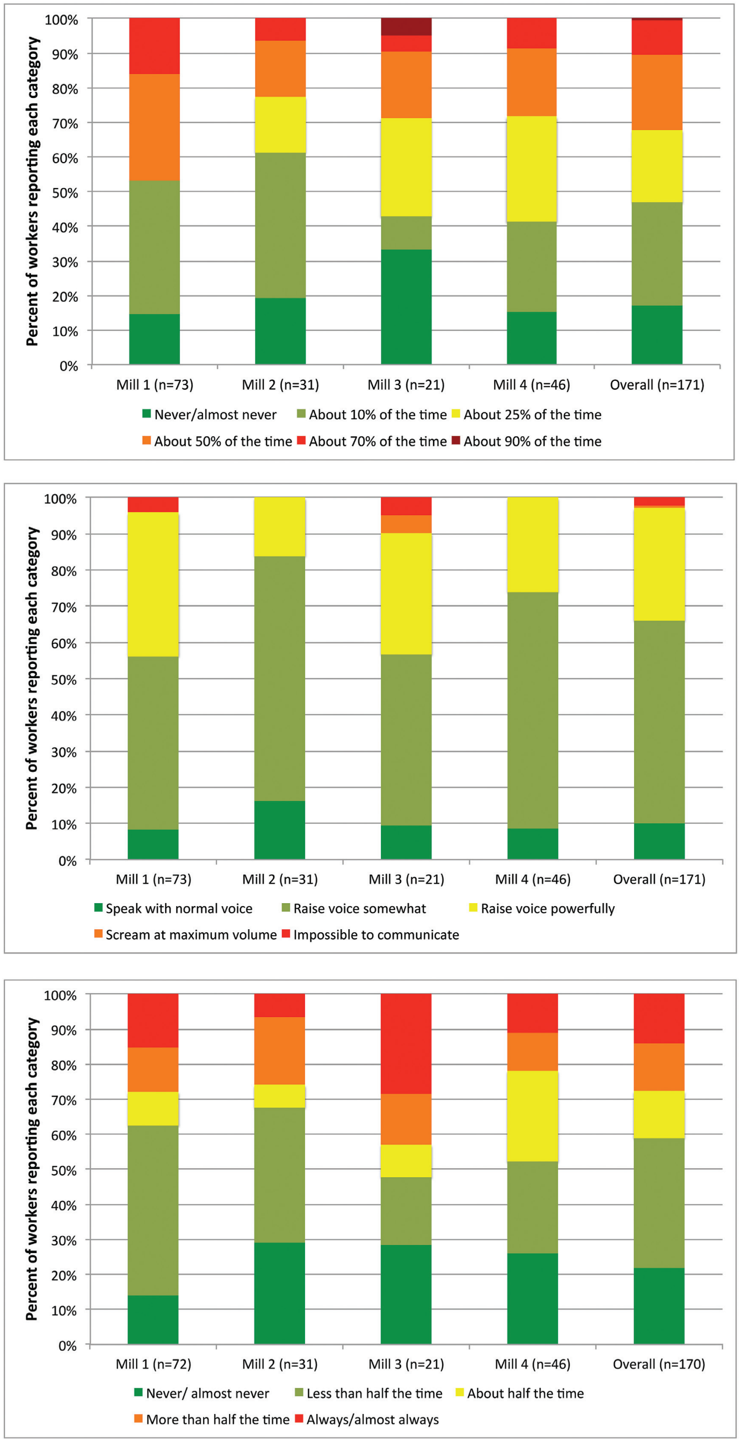


Figure 2 Distribution of perceived noise items (P) by mill and overall. (a) P1 Difficulty hearing. (b) P2 Speaking difficulty, and (c) P3 raise voice.

Table 3. Comparison of results from matched dosimetry and area measurements overall, by mill, and by operation, location, and job title within mill

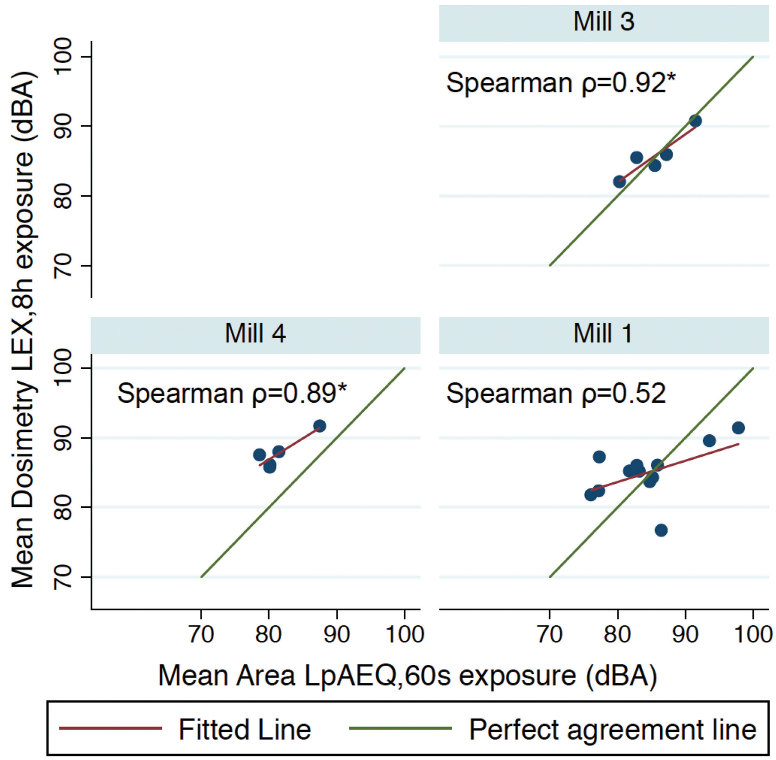
Grouping variable	*n*	Bias (Mean dosimetry $L_{EX,8h}$ – mean 60-s area L_{EQ}) (dB)				
		Mean	SD	Minimum	Maximum	% ≤5 dBA bias
Overall	209	1.5	5.5	−16.0	14.8	
Mill	162	1.3	5.3	−15.9	11.4	35.7
Operation	131	1.9	4.8	−12.5	14.0	30.3
Location	92	1.1	6.3	−15.0	14.8	20.4
Job title	94	2.1	4.2	12.5	13.3	22.2
Mill 1	75	0.04	5.9	−16.0	11.3	48.0
Operation	60	0.3	4.8	−12.5	9.7	42.5
Location	49	−0.4	7.4	15.0	14.8	29.9
Job title	50	1.6	4.1	−12.5	9.7	33.9
Mill 3	36	2.7	4.1	−5.1	10.4	31.5
Operation	33	2.1	4.9	−7.1	14.0	34.3
Location	21	−0.3	2.4	−5.2	4.1	28.8
Job title	21	−0.2	3.6	−7.1	10.4	27.4
Mill 4	51	2.4	4.9	−7.1	11.0	40.7
Operation	38	4.3	3.8	−3.8	13.3	25.6
Location	22	5.8	3.0	2.2	13.9	10.4
Job title	23	5.4	2.9	1.6	13.3	12.8

Area measurements not available at facility 2.

substantial amounts of time in the noisiest measured areas). Note that although the area measurements demonstrate differential bias, they nevertheless have a linear relationship with the dosimetry data and, presumably, the underlying true noise exposure, and are therefore appropriate to include in the Method of Triads analysis.

Figure 4 shows the relationship between the three perceived noise exposures and dosimetry noise levels (Fig. 4a–c) and between perceived noise exposures and area noise levels (Fig. 4d–f). Each of the three perceived exposure items showed an approximately linear relationship with dosimetry noise levels, and all showed weak to moderate but significant Spearman correlation coefficients of 0.3 or greater. Figure 4c (P3, *Raise voice*) shows a potential threshold effect at the 'Half of the time' category, suggesting that workers may stop trying to communicate in noise levels of this magnitude or higher, whereas Fig. 4a (P1, *Difficulty hearing*), shows no such effect. Relationships between the perceived exposure items and area measurements were less linear; only P1, *Difficulty hearing*, displayed an approximately linear increase in area noise levels with perceived exposure category. Based on these results, P1 was selected for further analysis.

The results of the Method of Triads analysis, conducted to achieve our second study objective, are shown in Table 4. The area noise grouping strategy used here was area measurements grouped by operation, which generally showed the lowest bias across the mills (Table 3). The two-way correlations between



* P<0.05

Figure 3 Comparison of mean noise dosimetry and mean area noise exposure estimates by matched location within mill.

the three measures were weak, ranging from 0.22 to 0.3, but all were highly significant. The estimated VCs, computed using Equations 1–3, ranged from 0.41 for area measurements to 0.70 for dosimetry measurements. The 95% confidence intervals for the estimated VCs (determined via bootstrapping), were narrow, suggesting that the estimates for each of the VCs were reasonably statistically robust. These results suggest that dosimetry measurements have the greatest validity in estimating the true underlying exposure to noise among the workers sampled. The VCs of perceived exposures and area measurements were substantially (28–43%) lower than that of dosimetry measurements. Validity coefficients could not be estimated for 141 Heywood Cases out of the 1000 (14.1%) bootstrap samples used to estimate 95% CIs. Twenty-four of these cases (2.4%) resulted from negative correlations between measurements, of which 21 were between area and perceived noise exposure measures. One-hundred seventeen additional Heywood Cases (11.7%) were due to VCs >1, of which 103 (10.3%) were associated with dosimetry.

DISCUSSION

Our study indicates that workers in Swedish paper mills have routine exposures to high levels of noise, as measured by dosimetry, area measurements, and survey measures of perceived exposure. In addressing the first objective of our study, which was to describe noise exposures among workers at the four participating paper mills, we identified a substantial potential for exposure to high levels of noise (i.e. dosimetry $L_{EX,8h}$ and area $L_{pAEQ,60s}$ measurements >85 dBA). Differences between the dosimetry and area noise measurements assigned to individual subjects were generally small, averaging +1.5 dB for dosimetry compared to SLM measurements, suggesting good overall agreement between these two objective measures of noise. However, for some operations within mill, differences in matched measurements were much greater (e.g. 4

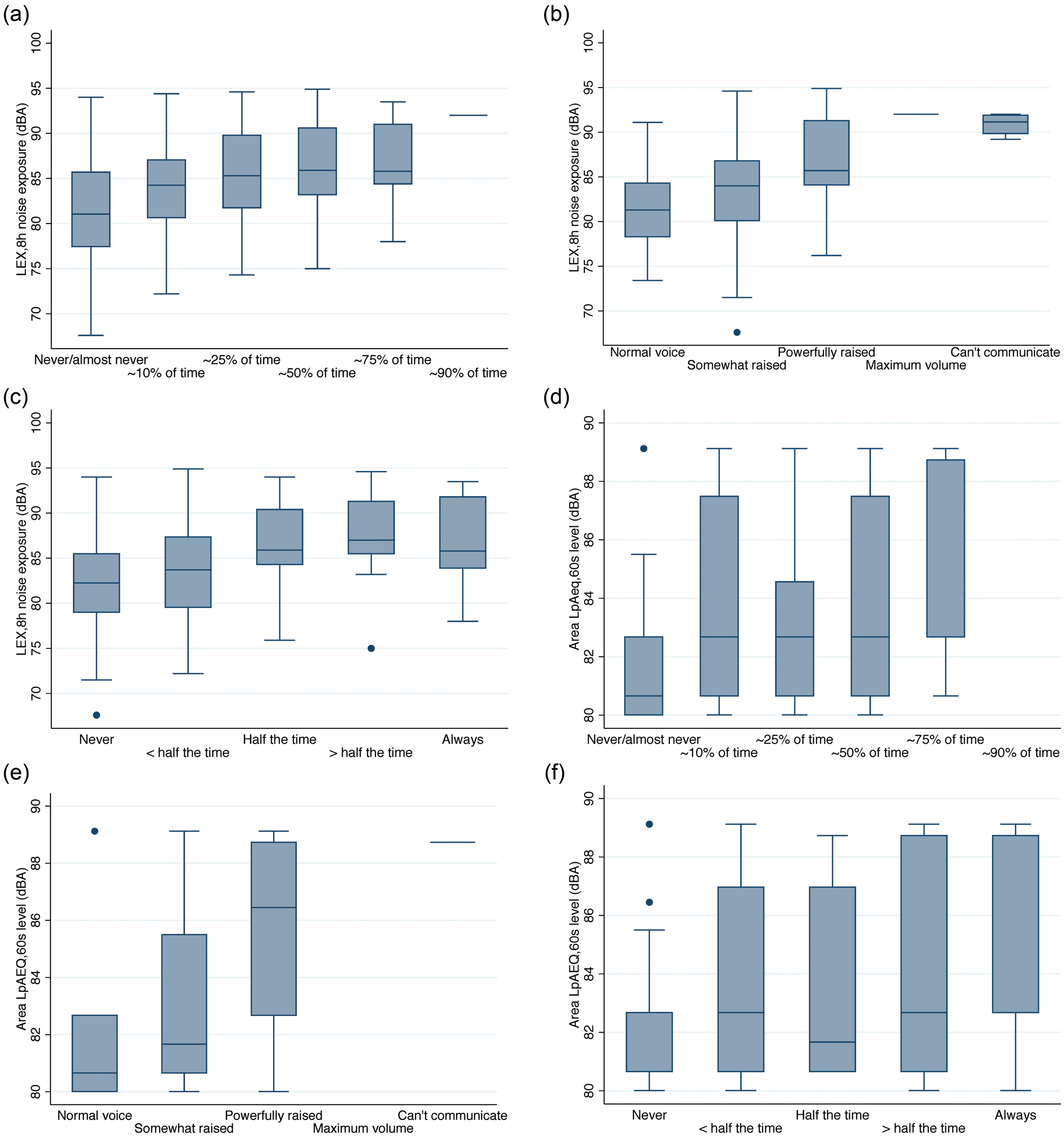


Figure 4 Perceived noise versus dosimetry ($L_{EX,8h}$) and area by operation ($L_{pAEQ,60s}$) levels. (a) P1, *Difficulty hearing* versus dosimetry ($N = 171$) Spearman $r = 0.32$, $P < 0.0001$. (b) P2, *Speaking difficulty* versus dosimetry ($N = 171$) Spearman $r = 0.35$, $P < 0.0001$. (c) P3, *Raise voice* versus dosimetry ($N = 170$) Spearman $r = 0.37$, $P < 0.0001$. (d) P1 *Difficulty hearing* versus area ($N = 171$) Spearman $r = 0.22$, $P = 0.02$. (e) P2 *Speaking difficulty* versus area ($N = 171$) Spearman $r = 0.35$, $P < 0.001$. (f) P3 *Raise voice* versus area ($N = 170$) Spearman $r = 0.15$, $P = 0.09$.

dB or more at mill 4), and individual pairs of dosimetry and area measurements in mill 4 showed the largest differences (more than 14 dB). Differences of this size indicate the potential for substantial measurement error for subjects working in some areas of paper mills, or conducting specific operations or jobs, a finding further reinforced by the large fraction of paired dosimetry and area measurements that differed by 5

Table 4. Method of triads results (n = 160)

Paired exposures	Correlation		Estimated validity compared to T	Validity	95% bootstrap CI[b]
	Coefficient	*P* value		Coefficient	
Dosimetry area	0.30	0.0005	Dosimetry	0.70	0.68–0.72
Dosimetry perceived[a]	0.28	0.002	Perceived	0.50	0.48–0.51
Area perceived[a]	0.22	0.02	Area	0.41	0.40–0.42

T, 'True' exposure.
[a]P1, Difficulty hearing item.
[b]Created from 1000 bootstrap samples.

dB or more. These large deviations between area and dosimetry measurements highlight the discrepancies that can arise if workers spend greater- or less-than-expected time in areas with exceptionally high or low measured noise levels, which can result in substantial positive or negative biases, respectively, when compared to dosimetry measurements. This reinforces the need for facility- and location-specific measurements and a noise exposure assessment strategy that involves a specific and consistent measurement protocol. The task-based and job-based strategies suggested in ISO 9612.1-2009 (ISO 2009) provide one such strategy, and include excellent guidance on methods that can be used to assess uncertainty and refine exposure assessments to maximize the accuracy of noise exposure estimates. While industries should not discard historical area and dosimetry-based noise measurements data, these data should be harmonized with the strategies advocated in ISO 9612.1-2009 in contemporary sampling campaigns to increase the accuracy and utility of noise exposure assessment efforts.

In further exploring noise exposures among Swedish paper mill workers, we evaluated perceived exposures from several survey items against objective dosimetry and area noise measurements. All of the items assessed showed linear and significant correlations with dosimetry measurements, though the results of P3, *Raise voice*, suggest a potential threshold effect. Only P1, *Difficulty hearing*, also showed a roughly linear association with area measurements, suggesting that workers can better differentiate noise levels in terms of the effort required to hear, rather than to speak. This item may be used to assess noise exposures among paper mill workers and identify workers who are potentially overexposed, though it is important to note that, while this measure agrees well with objective measures at the group level, it may work poorly for individual workers. One potential advantage of perceived exposure items is that workers may be able to mentally integrate time spent in different environments in a manner that would be challenging to mimic with area measurements or even dosimetry measurements. Previous research suggests that perceived noise exposures are not influenced by hearing ability at occupationally relevant noise levels (e.g. >80–85 dBA) (Neitzel *et al.*, 2009), but the validity of this assumption at lower noise levels has yet to be demonstrated.

We employed the Method of Triads to address the second objective of the study, which was to assess the validity of noise exposures evaluated by dosimetry, area measurements, and perceived exposure. Our results suggested that the measure with the highest validity compared to the unknown true exposure was dosimetry. This result was not particularly surprising, given the conventional treatment of noise dosimetry as the gold standard of exposure assessment. More surprising was the fact that the estimated validity of the perceived exposure measure exceeded that of objective area noise measurements. While dosimetry measurements demonstrated substantially higher validity, the difference between the estimated VCs for perceived exposure and area measurements was relatively small, suggesting that these measures may be expected to perform similarly in assessing workers' exposures, but highlighting the fact that the two measures should be calibrated against dosimetry data, ideally in each facility assessed. Use of perceived exposure measures alone for epidemiological studies cannot be recommended without population-specific validation of these measures, but our results do highlight the promise of properly-validated perceived exposure measures, which can often be collected more quickly and efficiently compared to—and at a fraction of the cost of—objective measures.

The levels measured here indicate that Swedish paper mill workers have potential for exposures in excess of those permitted by Swedish Work Authority regulation AFS2005:16 (Arbetsmiljöverket, 2005). The majority of noise exposures in in papermaking operations assessed by dosimetry at each of the participating mills exceeded the allowable $L_{EX,8h}$ limit of 85 dBA, and for several of the mills, a majority of exposures in converting also exceeded this limit. The Swedish occupational noise regulation requires that these workers be educated about the risk of NIHL from noise at these levels, that the workers use hearing protection devices provided by the employer, and that workers receive audiometric screening at regular intervals. Additionally, written plans must be developed to reduce exposures to below 85 dBA. At each of the participating mills, a comprehensive hearing conservation program addressing each of these requirements had been in place since prior to 2000. Acoustically treated control rooms and equipment enclosures, which resulted in reductions in worker exposures, were introduced at all four mills in the 1980s. However, there has been little focus on noise control since that time, and the current results suggest that additional emphasis on noise controls is warranted. For example, area measurements made inside most control rooms suggested little potential for hazardous exposure to noise, but dosimetry measurements on operators within these booths consistently indicated high potential for exposures >85 dBA. We believe this finding is due to the extended periods that workers sometimes spend outside of the control rooms servicing equipment and monitoring operations. Area measurements completely miss these exposures, while dosimetry and perceived exposures measures have the potential to effectively capture these exposures.

The noise exposures we identified among the paper mill workers assessed are generally consistent with the few previous studies of this industry. Toppila *et al.* evaluated over 400 paper mill workers in Finland using 10-min paired dosimetry measurements made inside and outside of workers HPDs. External L_{EQ} noise exposures ranged from 91 to 94 dBA (Toppila *et al.*, 2001), and the mean was 93 dBA (Toppila *et al.*, 2005). A study of over 100 workers in an Indian paper mill (Srivastava *et al.* 1994) found exposures of 80–96 dBA measured using an SLM. One study of workers in a Swedish paper mill found noise levels that were substantially higher than those measured here (Bergström and Nyström, 1986). A mean level for 94 dBA was reported for the workers studied, with a highest measured noise level of 100 dBA, but the method used to measure these levels was not described.

The results of our assessment of perceived noise exposure items generally agree with previous studies, as well. Several studies have found that perceived exposure items show reasonably good correlation with noise exposures measured via dosimetry (Ahmed *et al.*, 2004; Hagerman, 2013) or SLMs (Ising *et al.*, 1997; Koushki *et al.*, 2004). Our own previous study of Swedish office workers, teachers, and flight technicians showed good correlation between noise levels measured by dosimeter the lower response categories for item P3, *Raise voice*, (Neitzel *et al.*, 2014), and this same item showed good correlations with dosimetry measurements of noise exposure among construction workers (Neitzel *et al.*, 2009; Neitzel *et al.*, 2011a), as well as workers in manufacturing and warehousing operations (Neitzel *et al.*, 2009). Collectively, these studies demonstrate the utility of worker self-report for exposure assessment in workforces with high exposures to noise, though again such measures must be used with caution prior to validation.

This study has a number of limitations, the primary of which is the relatively small sample size for dosimetry and self-report measures. The generalizability of our results to other paper mills within Sweden, or to similar paper mill operations in other countries, may therefore be limited. However, as one of the intended objectives of the study was to inform our retrospective cohort epidemiological analysis of workers employed at these plants, generalizability was a secondary concern. The relatively small number of measurements collected with each method may also have violated some of the assumptions of the Method of Triads—that is, that errors in measures from each of the methods are uncorrelated, and the relationship with measures from each method and the underlying and unknown true exposure is linear and positive. However, we do not expect correlations in errors between the three quite different exposure assessment methods used, and the

95% bootstrap confidence intervals around the VCs for each method were narrow, suggesting that the random variability in the bootstrap samples was small and increasing our confidence in the VC estimates. Finally, one additional and potentially important source of error was present in the three types of measurements we collected: the temporal period assessed. Our dosimetry measurements were made over a single workshift, while area noise levels were measured over much shorter periods of 1 min, and our perceived noise items did not have a specific reference time but implied that the workers should consider their 'typical' exposures. The differing time periods used in these three methods introduces the possibility of error due to temporal misclassification, which would reduce the agreement between the three measures, and potentially the validity coefficients of all three, as well.

CONCLUSIONS

Our findings, when considered with those of previous studies, confirm that exposures to high levels of noise are common among paper mill workers. In describing these exposures using multiple measures (dosimetry, area measurements, and perceived exposures), and in comparing the estimated validity of each of these measures through a novel application of the Method of Triads, we have achieved the first and second objectives of the study, respectively. Collectively, these results achieved the third objective of the study, which was to inform the exposure assessment strategy for our ongoing retrospective cohort study of Swedish paper mill workers. Our results suggest that the use of the historical datasets of area noise measurements collected at several of the mills is possible, but that the relationship between area and dosimetry noise levels must be used to calibrate the area measurement data to increase its validity, or that, conversely, the area measurements are discarded in favor of personal measurement data or job- or task-based measurements made according to the protocols set forth in ISO 9612.1-2009 (ISO, 2009) Our results further highlight the potentially utility of perceived exposure survey items, but also reinforce the need for validation of these measures against objective data, ideally from dosimetry. This study sets the stage for analysis of the health risks associated with noise among Swedish paper workers in our ongoing study, and also suggests important opportunities for exposure assessment in other epidemiological studies that may employ multiple measures of noise exposures by estimating the validity of these measures using the Method of Triads.

ACKNOWLEDGEMENTS

This research was supported by AFA Försäkring grant 110104. The authors wish to thank Susanna Lohman for assistance with data collection, as well as the participating mills and their health and safety staff, as well as the participating subjects, without whose support this study would not have been possible.

DECLARATION FOR PUBLICATION

The authors have no competing interests to report.

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