A Questionnaire-Based Algorithm for Assessing Occupational Noise Exposure of Construction Workers

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Abstract

Objectives Occupational noise exposure is a major cause of hearing loss worldwide. In order to inform preventative strategies, we need to further understand at a population level which workers are most at risk.

Methods We have developed a new questionnaire-based algorithm that evaluates an individual worker's noise exposure. The questionnaire and supporting algorithms are embedded into the existing software platform, OccIDEAS. Based upon the tasks performed by a worker during their most recent working shift and using a library of task-based noise exposure levels, OccIDEAS estimates whether a worker has exceeded the full shift workplace noise exposure limit ($L_{Aeq,8h}$ ≥85 dB). We evaluated the validity of the system in a sample of one hundred construction workers. Each worker wore a dosimeter for a full working shift and was then interviewed using the OccIDEAS software.

Results The area under the under the Receiver Operating Characteristics (ROC) curve was 0.81 [95% CI 0.72 - 0.90] indicating that the ability of OccIDEAS to identify construction workers with a $L_{Aeq,8h}$ ≥ 85 dBA was excellent.

Conclusion This validated noise questionnaire may be useful in epidemiological studies and for workplace health and safety applications.

What this paper adds

What is already known about this subject?

- There has been no workplace noise exposure questionnaire available that has been validated against $L_{Aeq,8h}$ measurements using sound monitoring equipment.

What are the new findings?

- The online application, OccIDEAS, has been adapted to include questions on workplace tasks that create noise. Algorithms within the software use an inbuilt library of noise levels to determine a worker's $L_{Aeq,8h}$.
- In a population of construction workers OccIDEAS displayed excellent ability to identify workers who exceed their full shift noise exposure limit ($L_{Aeq,8h}$ ≥ 85 dBA).

How might this impact on policy or clinical practice in the foreseeable future?

- OccIDEAS is a valid measure to determine occupational noise exposure and may be useful in hearing loss prevention programs.

Introduction

Noise exposure is an ongoing worldwide occupational hazard.[1] Despite being a well-documented cause of hearing loss for over 300 years,[2] occupational noise is still responsible for 7-21% of all hearing loss worldwide.[1] Other health consequences such as tinnitus,[3] heart disease,[4] hypertension,[5] and mental health conditions[6] are also associated with increased noise exposure. To reduce the impact of occupational noise and plan effective prevention programs we need to understand how many workers are exposed, and within which occupations and industries this exposure occurs.

Compensation claims data,[7] hearing testing results from occupational health and safety surveillance,[8] noise surveys using sound monitoring equipment and questionnaire surveys have all been used to estimate the prevalence of hearing loss across different industries as well as identify high risk groups. However, as noise-induced hearing loss usually occurs over decades, hearing test results and claims are a poor indication of current workplace noise exposure levels.

Noise surveys using sound monitoring equipment are time consuming and costly. Noise surveys have predominately been undertaken in industries that are known to have high levels of noise exposure such as construction,[9] manufacturing,[10] agriculture,[11] and mining.[12] These survey populations may not be representative of the whole working population and noise surveys for some industries and occupations do not exist.

Questionnaire surveys are an established method of collecting population-based data.[13] The National Health and Nutrition Examination Survey (NHANES)[14] in the United States and the European Agency for Safety and Health at Work (EU-OSHA)[15] both included questions that ask workers to self-report workplace noise levels. NHANES asked 9,275 workers "At your current job, are you currently exposed to loud noise? [By loud noise I mean noise so loud you have to speak in a raised voice to be heard]".[14] However, none of the questionnaires for noise exposure assessment in large populations appear to have been validated against workplace noise measurements using sound monitoring equipment.

We have adapted an existing population-based exposure assessment application, OccIDEAS,[16] to include a questionnaire that will assess occupational noise exposure. The aim of the present study was to describe the OccIDEAS occupational noise exposure questionnaire and algorithm, and to determine its ability to discriminate whether or not a worker's full shift noise exposure ($L_{Aeq,8h}$) exceeded the 85 dBA exposure limit in a sample of construction workers.

Methods

i. OccIDEAS noise exposure questionnaire and algorithm development

OccIDEAS is an online application which uses questions about workplace activities to assess exposure to occupational hazards.[16] OccIDEAS was developed by Lin Fritschi and colleagues and has been used in research studies of carcinogens[17] and asthmagens[18]. OccIDEAS contains questions relating to usual tasks a worker undertakes. However, for noise assessment the standard measurement relates to noise occurring over a single work shift. We therefore developed questions and algorithms to assess the level of noise a worker experienced over their most recent working shift. We included questions about tasks performed (including tool use) during the participant's most recent working shift and the times associated with these tasks. Questions on the use of noise reduction methods (e.g. enclosed cabins on vehicles), background environment details, and shift length were also included within the questionnaire.

We incorporated an extensive library of task-based noise exposure levels ($L_{Aeq,T}$) into OccIDEAS. All workplace tasks included in the questionnaire have a corresponding $L_{Aeq,T}$ in the library. We derived the task-based $L_{Aeq,T}$ levels from a range of different sources including academic literature, occupational health and safety literature and websites, and online manufacturers' equipment specifications. If two or more sources were found for a particular task, the arithmetic means were calculated. All levels, including averages, were rounded to the nearest whole number. The final task based question in the interview asked participants if they performed any other noisy task that had not yet been mentioned. If they answered yes, they were asked to describe the task and to rate its noise level based on a subjective loudness rating scale developed by Williams et al.[19]

Noise from other workers undertaking tasks in the vicinity and noise emitted from plant equipment can add to an individual's noise exposure. To account for this, we included workplace characteristics and background noise environment questions into the questionnaire. Based on these answers, a background noise $L_{Aeq,T}$ was assigned for each participant.

At the conclusion of each questionnaire OccIDEAS generates a sound profile for the participant by tabulating all the partial noise exposures from each of the tasks performed during their most recent working shift with their corresponding time duration. Background noise is also included as a partial exposure in the sound profile. Table 1 shows an example sound profile of a participant from our study. From each participant's sound profile, the algorithm implemented in OccIDEAS estimates the $L_{Aeq,8h}$ using formulas outlined in the Australian/New Zealand Standard.[20] All partial noise exposures are estimated in terms of Pa^2h , using the formula: $E_{A,T_i} = 4.T_i.10^{0.1(L_{Aeq,T_i}-100)}$ where i represents each task, T_i the time associated with the task, and $L_{Aeq,Ti}$ the noise level in dBA preassigned to the task from the library. Using the equal energy rule that states for every 3 dB increase in noise exposure sound energy doubles,[21] all partial noise exposures ($E_{A,T}$) are summed ($E_{A,T} = \sum_i E_{A,T_i}$). The result is then normalised to an eight hour shift using the formula:

$L_{Aeq,8h} = 10log_{10}\left[\frac{E_{A,T}}{3.2 * 10^{-9}}\right]$. The result is then expressed in decibels.

Table 1. Sound profile of a participant who worked as an electrician (shift length = 8 hours)

Noise source	**Time (hrs)**	**$L_{Aeq,T}$ (dBA)**	E_{A,T_i} (Pa^2h)
Tasks performed / tools used by participant			
Manual tool used - hammer on metal	0.03	98	0.08
Manual tool used - hand saw	1	85	0.13
Power tool used - regular hand held drill	1	88	0.25
Power tool used - hand held grinder on metal	0.17	100	0.68
Total	2.20		1.13
Background noise			
Occasional loud noise from others using tools	5.80*	75	0.07
Total	8		1.21

Estimated $L_{Aeq,8h}$ = 85.8 dBA

*Background noise time = shift length (8hours) - equipment use time (2.20hrs)

The questionnaire and corresponding algorithms within OccIDEAS were specifically created to determine whether a participant had an $L_{Aeq,8h}$ equal to, or above 85 dBA in line with the Australian National Standard for Occupational Noise.[22] As a result, the questionnaire only included questions on tasks that emit an average $L_{Aeq,T}$ of 80 dBA or above. Tasks below 80 dBA contribute little to a worker's $L_{Aeq,8h}$ exceeding the 85 dBA limit and were therefore not included. To avoid calculating an estimate $L_{Aeq,8h}$ of 0 dBA, all participants were assigned a background noise level. These levels started at 65 dBA (no reported background noise) and ranged to 84 dBA.

The Australian Standard for Noise Exposure does not take into account any personal hearing protectors worn when calculating a worker's $L_{Aeq,8h}$.[23] While we collected data on the use of personal hearing protection, we did not incorporate this information into a worker's sound profile, consistent with the standard.

ii. OccIDEAS noise questionnaire validation study

Study population

One hundred workers from a range of construction occupations in Perth, Western Australia were recruited between March and August, 2015. The construction industry was selected as its workers undertake a wide variety of tasks, use a range of equipment, and work in a fluctuating background noise environment making it one of the most difficult industries to assess for noise exposure. To be included in the study participants had to be working in a building trade or on a construction site and have their management agree to their participation. Convenience sampling was undertaken with a view to include a range of occupations as well as a range of work environments (e.g. lone workers on domestic dwellings to those who work in teams on large construction sites). We identified construction companies and trades people through online searches and personal contacts. Companies or individuals were contacted by either email or phone call. Once the study procedure was explained, potential participants were asked if they would like to participate or, in the case of construction companies, permission to perform onsite recruitment was asked. We limited recruitment to no more than twelve participants from any one company or construction site. Construction workers were recruited on a first come first serve basis until 100 participants were enrolled in the study. Male and female workers of all ages were eligible. Only the inability to speak English excluded people from the study. The study was approved by the Curtin University Human Research Ethics Committee. Informed consent was obtained from all participants.

Noise assessments

Exposure to noise during the most recent working shift of each participant was assessed in two ways: by the questionnaire-based noise exposure assessment algorithm within OccIDEAS and by a dosimeter.

Participants wore a Bruel & Kjaer Type 4448 personal noise dosimeter for a full working shift. ISO settings with a 3 dB exchange rate were used in accordance with Australian Standards.[20] Interviewers (KL and KM) calibrated the dosimeter before each recording. They met with each participant before a shift to attach the dosimeter correctly to the workers' clothing, start the recording, and instruct the participant to not cover or remove the device. The dosimeters were placed on the shoulder in the hearing zone. We used Protector Type 7825 software to process the dosimeter results and calculate the $L_{Aeq,8h}$.[24] Dosimeter calibration occurred prior to reassignment to ensure drift had not occurred.

OccIDEAS was accessed by interviewers (KL and KM) using an electronic tablet with internet connection. Interviews were performed at the end of each participant's shift and were ten minutes or less in duration. The interviewers explained that the questions related to the tasks performed during the time they wore the dosimeter. OccIDEAS calculated the profile of exposure and $L_{Aeq,8h}$ automatically at the end of the interview with the results instantly uploaded to an online database.

Statistical analysis

Exposure to occupational noise was defined as dosimeter measurements of $L_{Aeq,8h}$ equal to or above the exposure level of 85 dBA. The sensitivity and specificity of OccIDEAS noise exposure assessment were determined with the dosimeter considered the 'true measure'. We calculated the Receiver Operating Characteristics (ROC) curve and the area under the ROC (AUC) to assess the ability of the OccIDEAS noise exposure assessment algorithm to discriminate between exposed and unexposed individuals. The ROC curve gives graphical representation of the sensitivity and specificity of the system at different cut points and also allows for the determination of an optimal cut-point.[25] The optimal cut-point for the limit of exposure estimated by OccIDEAS was identified at the maximum of the Youden-indices over all possible cut-points. The Youden-Index is defined as sensitivity+specificity-1[26] and was presented graphically in relation to possible cut-points. Positive and negative likelihood ratios were determined.

A sensitivity analysis was performed by removing those participants that participated in a noisy task that was not covered by the interview (and had to rate the noise level of the task on a scale).

Additionally we investigated the discriminative power of OccIDEAS when the limit of exposure estimated by OccIDEAS was set equal to or above 80 dBA and 90 dBA.

Results

i. *OccIDEAS noise exposure questionnaire and algorithm development*

Three hundred and three noise levels ($L_{Aeq,T}$) associated with construction tasks were found through searching the literature, websites and equipment specification sheets. After averaging the noise levels for similar tasks, 210 unique construction task based measurements were included in the OccIDEAS database. Nineteen of these noise levels were associated with saws, 21 involved welding or metal work and 11 were for tasks that involved non powered construction tools (e.g. hammers). Sixty unique $L_{Aeq,T}$ levels were included for tasks associated with operating construction vehicles including levels that distinguished between the effective use of insulated sound proof cabs (with no door or window open) for different vehicles.

ii. *OccIDEAS noise questionnaire validation study*

All participants were male, aged between 17 and 61 years [median 32 years, IQR 25 – 42 years] and were from 22 different construction occupation groups categorised by the Australian and New Zealand Standard Classification of Occupations (ANSZCO) (Table 2).[27]

Table 2. Size of company and occupation of study population - Construction workers in Perth, Western Australia (n = 100)

Characteristic	n
Size of company	
Micro business (1-4)	19
Small (5-19)	18
Medium (20-200)	41
Large (>200)	21
Missing	1
Occupation	
Electrician, electronic trades worker	20
Carpenter	16
Builder's labourer	13
Manager, building associate, safety officer	12
Plumber, gas fitter, air conditioning mechanic	13
Plasterer, tiler, floor finisher, painter, glazier	8
Bricklayer, stonemason	7
Scaffolder, steel fixer, metal fabricator	7
Crane operator, crane chaser	4

The shift lengths recorded by the dosimeter ranged from 4.4 to 12 hours [median 7.3 hours, IQR 6.6 - 8.1 hours]. The dosimeter $L_{Aeq,8h}$ results ranged from 71 dBA to 101 dBA [median 84.7 dBA, IQR 79.9 - 87.2 dBA]. Nearly half the study population (46%) had an $L_{Aeq,8h}$ dosimeter reading equal to or above 85 dBA.

The shift length determined by OccIDEAS ranged from 4 to 10 hours [median 7.5 hours , IQR 1.0 - 8.0 hours]. The $L_{Aeq,8h}$ estimated by OccIDEAS ranged from 62.9 dBA to 103.8 dBA [median 85.9 dBA, IQR 78.5 - 95.6 dBA] and 55% had an estimated $L_{Aeq,8h}$ equal to or above 85 dBA. The sound profiles generated by OccIDEAS demonstrated that 85% of participants undertook at least one task that had an associated $L_{Aeq,T}$ >= 80 dBA with an average of 3.25 tasks over this level undertaken during the recorded shift. Nineteen percent of participants used a construction vehicle or truck, 29% used a powered saw and 65% used a noisy manual (non-powered) tool. Eighty-two percent of participants reported working in a noisy background (not including radio noise) with 69% reporting that they had occasional tool noise in the background while they worked. Only two construction workers disclosed that they were around constant loud noise of others using very noisy tools (e.g. in the vicinity of someone using saw for most of the shift).

The ROC curve is shown in Figure 1. The AUC was 0.81 [95% CI 0.72 - 0.90]. The relationship between possible cut-points for the limit of exposure estimated by OccIDEAS and their respective Youden-index is shown in Figure 2. Maximum Youden-indices were observed at cut-points 85 dBA and 86 dBA. Table 3 shows the specificity, sensitivity, and likelihood ratios using these two cut-points. Although the 86 dBA cut-point had a slightly higher Youden-index (by 0.01) due to higher specificity, the 85 dBA cut-point had a 4.3% higher sensitivity.

Table 3. True positives, false positives, true negatives, false negatives and tests for diagnostic accuracy using the OccIDEAS cut-points of 85 dBA and 86 dBA (n=100)

	LAeq,8h OccIDEAS cut point	
	85 dBA	86 dBA
True positives	38	36
False positives	17	14
False negatives	8	10
True negatives	37	40
Sensitivity	82.6% (68.6% to 92.2%)	78.3% (63.6% to 89.1%)
Specificity	68.5% (54.4% to 80.5%)	74.1% (60.3% to 85%)
Positive likelihood ratio	2.62 (1.73 to 3.97)	3.02 (1.88 to4.86)
Negative likelihood ratio	0.25 (0.13 to 0.49)	0.29 (0.17 to 0.52)
Youden-index	0.51	0.52

The AUC representing the ability of OccIDEAS to discriminate between exposed and unexposed to an $L_{Aeq,8h}$ equal to or above 80 dBA was 0.80 [95% CI 0.71 - 0.90]) and for exposure to $L_{Aeq,8h}$ equal to or above 90 dBA it was 0.68 [95% CI 0.52 - 0.83]) (Supplementary figures S1 and S2).

Thirteen participants had partaken in a noisy task that was not covered by the questionnaire and rated the noise level of the task on a loudness rating scale. When these cases were removed from the analysis (n=87) the sensitivity using an 85dBA cut point increased to 84.6% (69.5% to 94.1%) and the specificity increased to 75.0% (60.4% to 86.4%).

Discussion

Based upon the classification of Hosmer and Lemeshow [28] the questionnaire with an integrated algorithm presented here has excellent but not outstanding ability (AUC =0.81) to identify construction workers with an $L_{Aeq,8h}$ exposure level equal to or above 85 dBA. The noise exposure questionnaire and assessment algorithm is incorporated into the existing software platform OccIDEAS, an established epidemiological survey tool which can be used in large cross sectional surveys.[17]

The Youden-index suggests that 85 dBA or 86 dBA are the two most suitable L_{Aeq8h} cut-points in OccIDEAS for determining if a construction worker has reached the 85 dBA $L_{Aeq,8h}$ exposure limit. The Youden-index for the 85 dBA cut-point is very similar to the 86 dBA cut point but has a higher sensitivity.

OccIDEAS also has excellent discrimination ability to distinguish workers who are exposed above the lower exposure limit of 80 dBA (AUC = 0.80). However, it has reduced ability to identify construction workers exposed above the higher exposure level of 90 dBA (AUC = 0.68). A possible explanation is that some task times given by participants may be an overestimation of the time the tool was making a noise. For example, when a participant reported using a circular saw for two hours it is possible the saw was only used for cutting a quarter of that time. This would lead to an overestimation of the $L_{Aeq,8h}$, pushing it over 90 dBA level when in fact it was less. The 85 dBA limit is affected to a lesser extent as even a short exposure is likely to put their $L_{Aeq,8h}$ over this level.

OccIDEAS estimated that 55 participants had an $L_{Aeq,8h}$ equal to or over 85dBA and dosimeter readings showed only 46 to have exposure over the limit. The sensitivity suggests that OccIDEAS is detecting those exposed over 85dBA but the lower specificity leads to more false positives occurring. The false positives may be due to participants overestimating the times of partial exposures.

Estimated shift lengths were similar to those recorded by the dosimeters. However, in four cases the shift lengths were underestimated by an hour or more as compared to the recorded dosimeter time. These participants may not have included work breaks in their estimate or the actual shift started later or finished earlier than when the dosimeter recording was started or stopped (due to safety briefing or time in the on-site office). Discrepancies in shift time would only be an issue if the unaccounted time included loud tasks that were not reflected in the participant's answers to interview questions. This is unlikely as the interviewers instructed the participant at the beginning of the interview that the questions relate to the entire time the dosimeter was worn.

Over the one hundred interviews, 325 construction tasks were recorded in the noise sound profiles. Only thirteen of these tasks did not have an associated $L_{Aeq,T}$ in the OccIDEAS library and the participant was asked to rate the loudness of these task on a scale. The removal of the thirteen interviews that contained these tasks resulted in an increase in the test's sensitivity and specificity using a cut off of 85dBA of 2% and 6.5% respectively. This suggests that using a noise scale to estimate a task's $L_{Aeq,T}$ is less accurate than using an $L_{Aeq,T}$ level derived from the literature. In particular, using the noise scale increased the number of false positives.

An advantage of using OccIDEAS is that it develops a sound profile for each participant. The sound profiles demonstrate the tasks undertaken that contributed to each participant's full shift exposure levels. This additional information will be useful for the design of hearing loss prevention strategies, particularly in industries such as construction where a wide variety of noise sources exist.

The OccIDEAS questionnaire relies on construction workers' recollection of tasks performed and the amount of time they spent on each task. Errors in the form of misclassification of tasks and equipment as well as the over or under estimation of time durations may have occurred. In addition, OccIDEAS relies on averaged task based noise levels from literature to predict partial exposures which could lead to errors in partial exposure levels. However, the use of follow up questions to refine task $L_{Aeq,T}$ estimates attempts to reduce this error. For example, if a participant reported they used a hand held grinder, questions about which material they ground were asked, which in turn modified the noise exposure estimate. Overall, despite these potential limitations, the estimate of whether the participant had exceeded the occupational limit was excellent.

A limitation of this study is that only a binary analysis of OccIDEAS performance was undertaken. In order to accurately predict those with $L_{Aeq,8h}$ under 80 dBA, OccIDEAS would have to also include questions relating to tasks that produced lower noise levels. L_{Aeq} levels of tasks below 80dBA are often hard to find or do not exist. As they represent only a minimal risk to hearing damage, they are rarely documented. A worker has to be exposed for 30 hours at 79 dB before their $L_{Aeq,8h}$ exceeds 85 dBA. As noise levels under 80 dBA only contribute minimally to a workers noise profile and the inclusion of such tasks would have increased the questionnaire length considerably, they were not included.

Although this validation study was conducted in the construction industry and therefore uses only questions specific to construction workers, OccIDEAS contains questionnaires for 51 occupational groups, designed to cover all possible occupations in a population. The questionnaire structure, the algorithms used to combine partial exposures and the techniques of categorising background noise are identical in other questionnaires available in OccIDEAS. The OccIDEAS noise exposure questionnaire and assessment algorithm may perform better in other industries where the tasks and emissions are more constant as there would be less recall error than in industries where tasks and emissions vary greatly.

We purposely chose the construction worker module for this validation study because this industry is known to have very complex noise environments and its workers also have a high risk of hearing loss. We recruited a diverse sample of construction workers to determine the ability of the OccIDEAS questionnaire system to work for a range of different noise profiles and construction noise environments. For example, we had managers on large construction sites who used no tools themselves and were only exposed to background construction noise; workers who used only one piece of equipment but used it all shift (e.g. excavator operator) and workers who used a wide range of tools (e.g. carpenter). We included those who worked alone (electrician doing repairs to a prebuilt building) and those who worked closely in a team (e.g. roofers or brick layers).

The $L_{Aeq,T}$ levels in the OccIDEAS database were collected from Australian and international sources. We do not foresee its use being limited to the Australian population, although some modifications for socio-cultural context of work may be needed. Although weather conditions and different climates could influence work behaviours, the system accounts for many of these influences. As an example, OccIDEAS will ask construction vehicle operators if a window or door of a seal cabin was open during the working shift and links the answer with the appropriate $L_{Aeq,T}$ level in the database.

Conclusion

The OccIDEAS noise questionnaire is a valid tool to identify construction workers with an $L_{Aeq,8h}$ equal to or above the exposure limit of 85 dBA. The OccIDEAS noise questionnaire is useful for epidemiological research and has further uses in the areas of noise monitoring and hearing loss prevention.

Figure 1. ROC curve showing the performance of OccIDEAS in identifying workers with $L_{Aeq,8h}$ ≥ 85 dBA

Figure 2. Youden index for different cut-points of OccIDEAS $L_{Aeq,8h}$ to estimate dosimeter $L_{Aeq,8h}$ ≥ 85 dBA

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Contributors: LF,KL,WW,JSH and IWL were involved in the study design, data analysis and interpretation. KL designed the noise algorithms under direct supervision of LF with advice from WW. KL and KM assembled the library of task based noise exposure levels and conducted the data collection. KL drafted this manuscript with advice from all other authors.

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