ORIGINAL ARTICLE

Predictors of hearing threshold levels and distortion product otoacoustic emissions among noise exposed young adults

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Aim: To examine the relations between noise exposure and other risk factors with hearing function as measured by audiometric thresholds and distortion product otoacoustic emissions.

Methods: A total of 456 subjects were studied (393 apprentices in construction trades and 63 graduate students). Hearing and peripheral auditory function were quantified using standard, automated threshold audiometry, tympanometry, and distortion product otoacoustic emissions (DPOAEs). The analysis addressed relations of noise exposure history and other risk factors with hearing threshold levels (HTLs) and DPOAEs at the baseline test for the cohort.

Results: The cohort had a mean age of 27 (7) years. The construction apprentices reported more noise exposure than students in both their occupational and non-occupational exposure histories. A strong effect of age and years of work in construction was observed at 4, 6, and 8 kHz for both HTLs and DPOAEs. Each year of construction work reported prior to baseline was associated with a 0.7 dB increase in HTL or 0.2 dB decrease DPOAE amplitude. Overall, there was a very similar pattern of effects between the HTLs and DPOAEs.

Conclusions: This analysis shows a relatively good correspondence between the associations of noise exposures and other risk factors with DPOAEs and the associations observed with pure-tone audiometric thresholds in a young adult working population. The results provide further evidence that DPOAEs can be used to assess damage to hearing from a variety of exposures including noise. Clarifying advantages of DPOAEs or HTLs in terms of sensitivity to early manifestations of noise insults, or their utility in predicting future loss in hearing will require longitudinal follow up.

Noise induced hearing loss (NIHL) of workers in high exposure industries (for example, foundry and textile workers, boiler makers) has long been recognised.[1] Collectively, results of such studies have been used to derive models of NIHL that estimate the distribution of hearing levels in populations exposed to continuous noise by noise intensity, duration of exposure and age.[2] However, in addition to occupational noise and aging, other factors, including gender, non-occupational noise exposure (for example, firearms use, recreational activities, music, and hobbies), exposure to ototoxic drugs or chemicals, and possibly pigmentation (hair and eye colour) may influence NIHL susceptibility and progression.[3 4] Additional unexplained variability in hearing loss must derive, at least in part, from yet to be described genetic factors affecting susceptibility to noise.[5] Despite the myriad studies documenting each of these sources of hearing loss, few studies have effectively considered the full range of potential risk factors in addressing the effects of noise exposure in a diverse adult population.

In most investigations of NIHL in human ears, noise effects are quantified using behavioural audiometric techniques.[6 7] However, there exists another non-invasive and sensitive metric of function, otoacoustic emissions (OAEs), that can provide important information concerning the status of the outer hair cells (OHC)—primary targets of high level sound.[8] Indeed, several investigators have suggested that OAEs may provide earlier indications of cochlear damage than standard pure tone threshold audiometry.[9–13] OAEs may be sufficiently sensitive to examine the relation between various risk factors and their effects on the hearing system, especially in prospective studies monitoring changes in function.[14]

Distortion product otoacoustic emissions (DPOAEs) are sounds that originate in active and highly vulnerable OHC based processes that underlie the excellent sensitivity and frequency selectivity of the normal cochlea. Distortion Product (DP) OAEs are produced by the normal cochlea when two pure tone "primary" signals, at frequencies f1 and f2 (f1<f2), are played to the ear simultaneously. The distortion product is generated in the cochlear regions where the travelling waves overlap.[14a] Numerous distortion products of the primary signals can be detected in the ear canal; however, the most robust, and therefore the distortion component used most often clinically, corresponds to the frequency, 2f1–f2.[8]

To evaluate the effects of noise and other exposures and risk factors on hearing, we have begun a five year prospective study of hearing loss in construction workers, monitoring function using both behavioural audiometric and distortion product otoacoustic emission (DPOAE) techniques. This report addresses audiometric hearing levels and DPOAEs in relation to a range of risk factors among our cohort at baseline.

METHODS

Subjects were recruited in 2000–01 through construction industry apprenticeship programmes in western Washington State, and at the University of Washington. All subjects were recruited during the first year of their apprenticeship or educational programmes and were expected to continue training in these programmes for four years or more. After a brief overview of the study purposes and procedures delivered at the training site, volunteers were asked to sign an informed consent letter approved by the University of Washington Institutional Review Board (IRB). The trades recruited were carpenters (including piledrivers and millwrights), bricklayers, cement masons, electricians, ironworkers, heat, frost and

Abbreviations: ANSI, American National Standards Institute; DPOAE, distortion product otoacoustic emission; HPD, hearing protection device; HTL, hearing threshold level; NIHL, noise induced hearing loss; OAE, otoacoustic emission; OHC, outer hair cells

Main messages

- Among a group of relatively young construction workers and students, HTL was strongly associated with age and years of work in construction. Other noise exposures including other noisy occupational exposure, firearms use, and recreational exposures were less consistently related to hearing level.
- Similar patterns of risk factors were observed in relation to decrements in DPOAEs.
- The greatest effect of occupational noise exposure was observed at 4, 6, and 8 kHz for both HTLs and DPOAEs.
- In multivariate mixed models including all significant risk factors, each year of construction work was associated with a 0.7 dB increase in HTL and a 0.2 dB decrease in DPOAE amplitude.

Policy implications

- Construction workers, even within the first few years of work, are at risk of noise induced hearing damage. More effort is required in helping young construction workers avoid noise exposure and prevent this early damage.
- Although non-occupational exposures contribute to hearing damage, occupational exposures, especially in construction, is among the strongest predictors of hearing level. Prevention strategies must continue to focus on work related noise, while also addressing non-occupational factors.
- DPOAEs are an effective tool for monitoring early damage induced by noise exposure, showing similar patterns of effect as audiometric hearing thresholds. The sensitivity and predictive utility of DPOAEs in this application will require additional longitudinal study.

asbestos workers, sheet metal workers, and operating engineers. Graduate students in the first year of medical or doctoral degree programmes were solicited at the University of Washington.

All testing was conducted at the apprenticeship training sites during training days, or at the university for students. Tests including questionnaire, audiometry, and DPOAE were conducted sequentially for each group of apprentices in order to minimise the interruption of classes. Volunteers were paid a small monetary incentive for their participation.

An extensive questionnaire concerning demographics, medical and otologic history, family history of hearing loss, and detailed questions concerning occupational and non-occupational noise exposure histories was developed after a review of both occupational, environmental, and personal characteristics that could affect hearing level.[3–5] The work histories included the timing and duration of all construction jobs, specific construction tasks and tools, use of hearing protection devices, and type of construction environment. Occupational exposure to both firearms and machinery/vehicle noise during military service was assessed independently from other occupational and firearms exposures. The histories also solicited information on all non-construction jobs involving exposure to high noise levels, subjectively defined as having to raise one's voice to be heard at arm's length. The questionnaire was delivered with a computer assisted personal interview, and responses were entered directly into an MS Access database.

Hearing evaluation included pure tone air conduction threshold audiometry and distortion product otoacoustic emission tests delivered by field staff after training by the study audiologists. Otoscopic examination and tympanometry were used to screen subjects prior to testing. If excessive/obstructive cerumen was observed, or if tympanometry revealed findings consistent with tympanic membrane or middle ear abnormality (see tympanometry methods), subjects were referred for appropriate treatment and asked to return for testing at a later date. Subjects were also asked during screening if they had experienced any substantial noise exposure within the past 16 hours, in an effort to control the potential for a temporary threshold shift to affect the results.

Tympanometry was conducted (Grason Stadler, Model GSI 38) in the right and left ear sequentially. Tympanograms were recorded over the pressure range +200 to −400 daPA using a 226 Hz probe tone. Ear canal volume, compliance peak, and pressure at maximum compliance were recorded for each ear. Non-intact tympanic membranes or tests indicating pressures more negative than −100 daPa were interpreted as outside the normal limits for middle ear function, and the corresponding hearing tests were excluded from analysis.

Pure tone air conduction behavioural threshold testing was conducted in a mobile, acoustically treated audiometric test van by audiology technicians (Washington Audiology, Inc., Seattle, WA) certified by the Council for the Accreditation of Occupational Hearing Conservationists (CAOHC). Background noise levels in the test van were monitored throughout each testing session using a Quest Bioacoustics Monitor. The test environment met OSHA requirements for audiometric test facilities[15] during all tests, and was in most cases compliant with the more stringent ANSI standard (S3.1-1991) recommended by the National Hearing Conservation Association for audiometric test facilities.[16] Audiometry was conducted on up to six subjects at a time using a Tremetrics RA300 audiometer with TDH-39 headphones and an automated test sequence at 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz. Audiograms with mean thresholds greater than 50 dB HL at 500, 1000, and 2000 Hz were excluded from the analysis in order to limit the analysis to those without pre-existing conditions probably unrelated to noise exposure. Audiograms were also reviewed by an audiologist and subjects with abnormal findings were referred for follow up clinical consultations.

DPOAEs were measured using a Bio-Logic Scout AuDX system in a quiet room. DPOAEs corresponding to the frequency 2f1–f2 were recorded as ''DP-grams'' (21 log spaced f2 frequencies between 1031 and 10 028 Hz; $f2/f1 = 1.2$; $L1 = 65$ dB SPL; $L2 = L1–10$). At seven f2 frequencies chosen to approximate the audiometric test frequencies, DPOAEs also were recorded as functions of increasing stimulus level ($L1 = 35–80$ dB SPL in 5 dB steps; $L2 = L1–10$). During DPOAE tests, noise levels in the test room were monitored with a Quest Q-300 type II data logging noise dosimeter, which indicated one minute Leq levels of 66.7 ± 6.3 dBA. These environmental conditions were adequate given the attenuation provided by the OAE ear plug mounted probe, and the collection of the noise floor levels in the ear canal by the system. Noise floors measured in the ear canal averaged from −25 to −5 dB SPL, depending on frequency.

All instruments received annual calibrations in accordance with manufacturers' specifications. Prior to each test session, each instrument was checked and calibrated for proper response following recommended protocols.

Regression models were developed to characterise the relations between risk factors (demographics, noise exposures, and non-noise exposure factors) and hearing/cochlear status, as characterised by audiometric hearing threshold levels (HTLs) in dB HL and DPOAE levels (in dB SPL) recorded in response to the $L1 = 65$, $L2 = 55$ dB SPL primaries. Models were developed for each hearing test for 2, 4, 6, and 8 kHz only, in order to simplify the results while still showing effects across a range of frequencies. Modelling of DPOAEs to lower level primaries was not attempted because a larger fraction of those data was obscured by the noise floor. Linear mixed effects models were run including a random effect for subject, to control for correlation between ears. Generalised additive models were also used during the model development procedure in order to examine the functional form of the covariates.

Modelling proceeded in several steps. First, a set of primary covariates including age, gender, dominant sided ear (same side as dominant hand), family history of HL, and years of construction and noisy non-construction work were included in an initial model predicting 4 kHz HTL. These variables were selected a priori on the basis of a belief that they would likely be important in predicting hearing.

Secondary covariates (for example, race, smoking, military, and hobby noise exposures) were then tested individually for inclusion in the modelling procedure. They were retained for further modelling if the p value for the added covariate was <0.2. Each of the primary and secondary covariates tested in this way are defined in table 1.

Next, the continuous primary variables and those secondary covariates that had $p < 0.2$ were included in an additive model (GAM) as smooth functions defined by a four degrees of freedom smoothing spline. GAM plots, plots that show the contribution of the continuous covariate to its additive predictor, were run for each variable in order to visualise the best functional form for each covariate. On the basis of these plots, some variables were re-coded to produce a parsimonious linear model.

In a few cases, individual subjects were identified as clear outliers, producing highly non-linear effects in specific covariates. Dummy variables were created for these subjects in order to preserve their contribution to the analysis while limiting their individual effect on covariate coefficients. Because it is not good practice to selectively remove data that are inconsistent with a model, we felt that including them as outlier adjustments was more advantageous than removing them from the analysis altogether.

Using this final list of candidate predictor variables, reduced models were selected using a backward stepwise elimination procedure with $p > 0.1$ for exclusion. If a variable associated with one of the individual outliers was removed from the model, the dummy variable for that individual was also removed. Finally, to check for possible residual confounding, each of the eliminated covariates was reintroduced one at a time. If reintroduction changed the coefficient for any primary covariate by more than 10%, it was retained in the model.

RESULTS

The number of subjects and ears tested, and included in the analysis is presented in table 2. A total of 456 subjects were given baseline questionnaires and 912 ears were included in audiometric testing. Eighty six per cent of these cases were construction apprentices. Sixty one ears from 43 subjects were excluded based on otoscopic observation of interfering/obstructive cerumen or tympanic membrane/middle ear abnormalities evident on tympanometry. An additional eight ears from six subjects were excluded because of significant

Table 1 Definition of primary and secondary variables

Variable	Units or category labels	Definition
Primary		
Age	Years	Age at baseline test
Gender	Yes/no	Yes if male
Dominant sided ear	Yes/no	Yes if ear is same side as dominant hand
Family history	Yes/no	If family member had unusual HL
Construction work	Years	Years of work in construction industry
Non-construction work	Years	Years of work in non-construction jobs with high noise exposure
Secondary		
Race	Yes/no	Yes if Caucasian
Brown eyes	Yes/no	Yes if brown
Dark hair	Yes/no	Yes if black, brown, dark brown
Firearms, military	Years	Years of regular* military use of firearms or exposure to blasts/explosions
Firearms, non-military	Years	Years of regular* non-military firearm use
Machinery, military	Years	Years of regular† exposure to heavy machinery in the military
Machinery, non-military	Years	Years of regular† use of heavy machinery at home
Power tools	Hours/week	Average hours per week spent using power tools at home
Motorcycle use	Years	Years of regular* motorcycle riding
Other vehicles	Yes/no	Yes if regular* use of snowmobiles or piloting aircraft
Loud recreation	Yes/no	Yes if regular (at least several times monthly) attendance at concerts, dances, races, or sporting events
Loud music	Yes/no	Yes is listen to music at ''loud'' levels
Smoking status	Current, ex, never	Smoking status category at baseline test
Disease	Yes/no	Yes if any of the following were self reported: arthritis, kidney disease, meningitis, mumps, diabetes, autoimmune diseases, hypertension, high cholesterol, cardiovascular disease, scarlet fever, neurological or seizure disorders, otoschlerosis, or Meniere's disease
Ear trauma	Yes/no	Yes if report of ear surgery (include P/E tube placement), or ear injury (including damage due to explosions or blasts)
Ototoxic therapy	Yes/no	Yes if history of intravenous antibiotic therapy within 6 months prior to test, chemotherapy within 6 months prior to test, antimalarials (quinine or chloroquine) within 48 hours prior to test or diuretics (Edecrin or Lasix) within one week prior to test
Aspirin	Yes/no	Yes if within 24 hours prior to test
Solvents	Years	Years of frequent exposure to solvents on or off the job
Paints	Years	Years of frequent exposure to oil based paints on or off the job

*Regular defined as at least several times weekly.
†Regular defined as at least daily.

low frequency hearing loss, indicative of a pre-existing non-noise induced hearing loss. As a result of these exclusions, this analysis includes 436 subjects with valid tests in at least one ear, for a total of 843 ear specific tests, 723 of which were from construction apprentices.

Demographic and risk factors addressed in this analysis are presented in tables 3 (continuous variables) and 4 (categorical variables). The average age of the two groups was the same, 27.2 years (range 17–57 years). The apprentices were mostly male (89%), while about half of the students were female. Both groups were about 80% self reported Caucasian and about 90% right handed. Only one student was a current smoker, while almost half the apprentices reported current smoking, and another 17% were ex-smokers.

Substantial differences were observed in the two groups with respect to exposure to noisy activities—both work and non-work related. Apprentices had on average over two years of previous work in construction (despite having been selected at the outset of their apprenticeship training) compared to almost zero years of previous construction work for the students. Both groups reported between three and four years of previous non-construction noisy work. Apprentices, however, also reported greater firearms use, machinery and power tool use at home, years of riding motorcycles, listening to loud music, and regularly participating in loud recreational activities such as concerts and sporting events.

When asked about high noise exposure within the 16 hours prior to the test, 87.6% reported no prior noise exposure, 8.2% had noise exposure but reported use of hearing protection, and 4.3% reported exposure without protection. Inclusion of pretest noise exposure in the risk factors models showed no contribution to the results, suggesting that no substantial TTS was present.

Average HTLs, with population standard deviation error bars, are presented by group in fig 1. As a group, the students showed only slight increases in average HTLs at 6 and 4 kHz: 13.5 and 5.8 dB, respectively. In comparison, the apprentices had somewhat higher average HTLs at 6 kHz (18.3 dB) and 4 kHz (12.2 dB). The variability in HTLs among both groups was fairly large, with standard deviations of about six decibels at 500 and 1000 Hz, rising to about 15 dB in apprentices and 11 dB in students at 6000 Hz.

Average DP-grams for the two groups are shown in fig 2. Three important observations can be made about the figure. First, DPOAE levels are smaller in apprentices than in students across the frequency range 3000 and 8000 Hz—the region primarily affected by noise exposure. Second, there is a very high degree of variability in the DPOAEs—with standard deviation of about 7 dB in this same region and up to about 10 dB at the lower frequencies. Finally, even for moderate level primaries ($L1 = 65$; $L2 = 55$ dB SPL), a substantial portion of the population's DPOAEs are below the noise floor above about 8000 Hz. It should be noted that a substantial amount of the observed variability can be explained by age and other factors, and is addressed in the multivariable analyses below.

DPOAEs are further described by the series of I/O plots in fig 3, in which similar trends can be seen. Little difference can be seen between the two groups at lower (2 and 3 kHz) and higher (8 and 10 kHz) f2 frequencies; however apprentices have smaller average DPOAEs in the 4–6 kHz region. Furthermore, the difference between the two groups is an almost constant 3–4 dB over the full range of stimulus intensities from about 40 to 80 dB SPL. At the lower stimulus levels, a large portion of the DPOAE response is buried in the noise floor for both groups, and the sound pressure level at which the response becomes obscured increases as the frequency increases. For example, the average DP intersects with the noise floor at about 35 dB for 4 kHz, but at around 55 dB for 8 or 10 kHz stimuli.

Multivariable mixed effects models for describing the variability in HTL were developed first for the 4 kHz HTL. A random effect variable for subject was included to control for non-independence between ears. The development of this initial model is presented in table 5. Inclusion of the primary variables age, gender, dominant sided ear, family history, and years of construction and non-construction noisy work (model 1) produced a model fit statistic (AIC) of 6513, and highly significant coefficients for age, gender, and construction work. Addition of all other potential risk variables that had a $p < 0.2$ when added to the model independently (model 2), improved the overall model fit slightly ($AIC = 6505$). The additional variables that contributed significantly to this model ($p < 0.1$) included a history of otologically relevant disease, years of machine exposure in military service, and years of paint and solvent exposure.

This model was then refit using an additive model and GAM plots constructed for HTL versus each independent variable. After examining the GAM plots, several covariates were categorised. Age was classified into four 10 year age groups (<20, 20–29, 30–39, and ⩾40) to allow for an almost flat response curve under the age of 30, and a relative linear increase in relation to age above 30. Use of firearms outside the military was recoded as a binary variable (ever/never) to adjust for the apparent small difference between firearms users and those reporting no firearms use, and a relatively flat response curve across a wide range of firearms' use history. Regular use of motorcycles was also recoded as a binary variable (ever/never) to address a complex pattern of apparently rising thresholds up to about 15 years of use, and a reversal of this pattern among the 13 individuals who reported longer use. In addition, intercepts were added for four individual subjects. Subject A was an outlier for construction work, subject B for machine exposure in the military, subject C for non-military machine use, and subject D for power tool use. Subject A had much worse hearing than expected with the model, and the other three had much lower (that is, better) HTLs than expected.

After recoding these variables, the model (model 3, table 5) produced a substantially improved fit statistic ($AIC = 6439$). Finally, a backwards elimination procedure was run to eliminate all variables with $p > 0.1$, resulting in a final reduced model for 4 kHz HTL with a mildly poorer fit

Table 2 Number of baseline tests completed

	Apprentices		Students		Total	
	Subjects	Ears	Subjects	Ears	Subjects	Ears
Questionnaires and audiometry	393	786	63	126	456	912
Excluded for middle ear problems	38	55	5	6	43	61
Excluded for low frequency loss	6	8	0	0	6	8
Audiometry tests included	374	723	62	120	436	843
OAE tests included	372	720	62	120	434	840

Table 3 Cohort demographics and risk factors (continuous variables, mean (SD))

Characteristic	Apprentices (n = 374)	Students (n = 62)	Total (n = 436)
Demographic factors			
Age	27.2 (7.0)	27.2 (4.2)	27.2 (6.7)
Noise exposure factors			
Construction work (years)	2.2 (3.2)	0.2 (0.8)	1.9 (3.1)
Non-construction noisy work (years)	3.8 (6.0)	3.4 (4.8)	3.7 (5.9)
Regular firearm use (years)	2.2 (5.1)	0.0 (0)	1.9 (4.8)
Firearms/explosion in military (years)	0.2 (1.0)	0.01 (0.06)	0.2 (0.9)
Power tool use (hours/week)	2.2 (4.1)	0.4 (0.5)	2.0 (3.9)
Home machinery use (years)	0.5 (2.8)	0.1 (0.6)	0.5 (2.6)
Machine use in military (years)	0.4 (1.8)	0.2 (1.0)	0.4 (1.7)
Motorcycle use (years)	2.1 (4.8)	0.1 (0.5)	1.8 (4.5)
Other exposure factors			
Solvent exposure (years)	1.3 (3.4)	0.9 (2.1)	1.3 (3.2)
Paint exposure (years)	0.5 (1.6)	0.0 (0.1)	0.4 (1.5)

(AIC = 6475) due to the large number of variables excluded from the model. During model development, the value of the coefficients remained similar from model to model, providing some reassurance that the results were not highly biased by the procedure used.

Backwards elimination of these same variables was then conducted for audiometric HTLs at 2, 6, and 8 (in addition to 4) kHz, and the corresponding DPs (f2 = 2014, 3936, 6279, and 7965 Hz); the final reduced models are presented in tables 6 and 7, respectively. The categorised age variable was significant ($p < 0.05$) for all eight models, showing small increases in HTLs and decreases in DP levels during the 20 s, somewhat more during the 30 s, and a large effect after age 40. Males had 5–6 dB higher HTLs at 4 and 6 kHz and a significant decrease in DPs at all frequencies. Dominant ear (same side as dominant hand) had better thresholds (at 2, 6, and 8 kHz) and larger DPs (at 2 and 6 kHz), and a family history of hearing loss was associated with a 3 dB increase in the 6 kHz HTL.

Years of construction work was significantly ($p < 0.05$) associated with increases in HTL from about 0.5 to 0.7 dB per year over the range 4–8 kHz. At the same frequencies, construction work predicted decrements of DPs of about 0.2 to 0.4 dB per year. Other sources of noise exposure including regular use of firearms, power tool use, and motorcycle riding contributed to loss of hearing function only at selected frequencies (see tables 6 and 7). Interestingly, both years exposed to solvent based paints and years exposed to solvents were associated with changes in hearing at 2 and 4 kHz. However, they exhibited opposite effects on hearing; painting history predicted a small improvement at 4 kHz (HTL) and 2 kHz (DP) of less than 1 dB per year, while solvent use predicted the opposite, especially at 4 kHz.

DISCUSSION

The current analysis shows the well known effect of occupational noise exposure on hearing levels at 4 and 6 kHz in a population of relatively young adults in the construction industry. The measured effect was about 0.7 dB loss in threshold sensitivity for each year of work in the industry, after controlling for the effects of age, gender, and a multitude of other risk factors commonly present among contemporary working populations. Of particular note is the fact that this finding is paralleled by a 0.2 to 0.4 dB

Table 4 Cohort demographics and risk factors (categorical variables)

	Apprentices (n = 374)		Students (n = 62)		Total (n = 436)	
Characteristic	Number	%	Number	%	Number	%
Demographic factors						
Gender: male	333	89	34	55	367	84
Race/ethnicity: white	292	78	50	81	342	78
Cigarette smoker						
Current	180	48	1	2	181	42
Ex	65	17	4	6	69	16
Never	129	34	57	92	186	43
Family history of HL	83	22	18	29	101	23
Handedness: right	329	88	57	92	386	89
Eye colour (brown)	151	40	25	40	176	40
Hair colour (dark)	282	75	48	77	330	76
Noise exposure factors						
Ever regular firearms use	84	22	0	0	84	19
Other vehicle use	53	14	1	2	54	12
Loud recreation	81	22	10	16	91	21
Listen to music loud	113	30	3	5	116	27
Other exposure factors						
Previous disease	83	22	18	29	101	23
Ear injury	72	20	8	13	80	18
Ototoxic therapy	14	4	0	0	14	3
Aspirin use	36	10	2	3	38	9

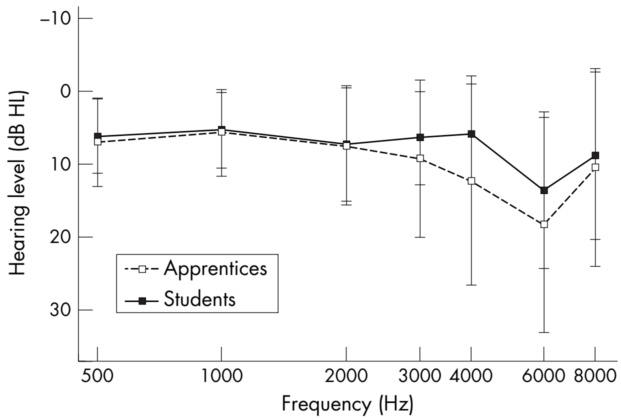

Figure 1 Hearing threshold levels by exposure group. Error bars represent ±1 standard deviation.

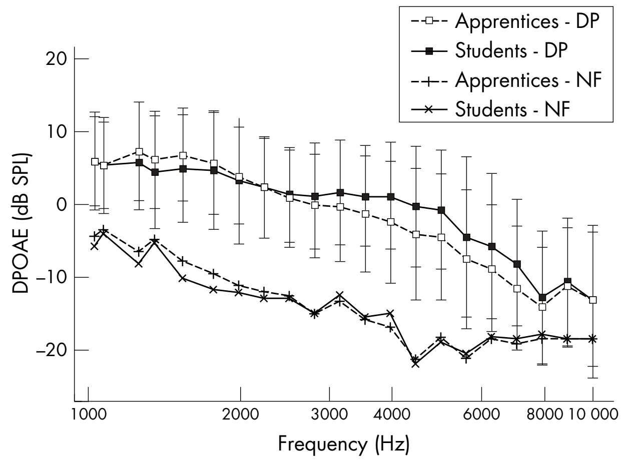

Figure 2 Distortion product otoacoustic emissions (L2 = 65 dB) DP-gram by exposure group. Error bars represent ±1 standard deviation.

decrease in DPOAE level at similar frequencies for each year of work. These effects were observed in a relatively young adult population of beginning construction apprentices and graduate students with an average of less than 2 years of construction work and 4 years of other noisy work experience.

It is interesting to note that the largest decrease in hearing thresholds was observed at 6 kHz and the coefficients for both noise and age were very similar at 4 and 6 kHz. Observation of noise notches centred around 6 kHz in the audiogram is a common finding; however, the degree to which such notches are noise related remains uncertain.[17] It is possible that the high impulse characteristics of construction industry noise results in damage at somewhat higher frequencies than typically seen in industries with more continuous noise patterns.

With the exception of age, past work in construction was the most consistent predictor of hearing level. Noise exposure levels in construction commonly exceed 85 dBA, and are characterised by a high degree of impact noise and intermittency.[18 19] In our studies, we have also observed the use of hearing protective devices to be rare—less than 15% of total work time,[20] and on average, only 30% of time spent over 85 dBA. This combination of high exposure levels and low HPD use clearly places construction workers at relatively high risk of NIHL. Despite our prior expectation, work in other "noisy" workplaces did not enter the risk models. This is likely due to misclassification resulting from the subjective reporting of "high" noise in the work environment.

Regular use of firearms, which is a well known non-occupational risk factor for NIHL,[21 22] was associated with a 2.7 dB decrement in HTL at 4 kHz, a finding similar to that reported elsewhere.[23] Typically, gun shooters lose hearing in the ear on the side of their non-dominant hand, which may explain why firearms use predicted an increased threshold at 4 kHz, while dominant sided ear was associated with a lower threshold at the other three audiometric frequencies. Similar handedness effects have been found previously in an older population.[24]

Motorcycle use was associated with an almost 3 dB increase in hearing thresholds at 6 kHz and a 1.4 dB decrease in DPs at 8 kHz. Use of power tools at home was associated with a small (0.2 dB per year) decrease in DPs at 6 kHz. These small but significant effects have been shown elsewhere,[25 26] and the effects are in the expected direction, but are not consistent across potentially noise affected frequencies, and are again hampered by imprecisely measured variables.

There is increasing evidence showing the ototoxic properties of solvents, especially aromatics such as styrene and toluene.[27 28] Self reported regular exposure to solvents was associated with 0.6 dB per year increase in hearing threshold at 4 kHz, as well as a 0.25 dB per year decrease in DPs at 2 and 4 kHz. While very consistent with the literature, this observation is based on an average of less than 1.3 years reported solvent exposure and requires further exploration.

Our study is among the first to consider risk factors associated with DPOAEs among a population of working young adults. Sallustio *et al*, for instance, analysed hearing data on a group of 140 factory workers, using audiometry and DPOAEs, in addition to several other tests of auditory function.[9] Although a clear relation between DPOAEs and HTLs was shown, the analysis only compared groups divided by current noise level and audiometric findings, and included no multivariable risk factor models. In contrast, we have compared a wide range of risk factors, using a multivariable regression model selection procedure to identify those factors most clearly associated with HTLs or DPs. The independent effects of multiple exposures or risk factors can only be addressed in a population based sample through the use of multivariate modelling.

On an absolute scale, the variability of DPOAEs observed in this study was considerably higher than the variability of the HTLs. While such an observation could suggest that the measure is less precise, it is also possible that the DPOAE measures are more sensitive to interindividual differences, and thus may be more indicative of subtle changes induced by noise and other environmental influences. In preliminary analyses of repeated tests on our subjects, test retest standard deviation is under 3 dB at frequencies less than 8 kHz (and l1 = 65 dB), consistent with the values in the literature[29] and less than that normally associated with pure tone audiometry measured in 5 dB steps. Nevertheless, even though our results do not suggest that DPOAEs have any particular advantage over thresholds—in terms of identification of risk factors, or sensitivity to specific insults—they do show a striking degree of consistency in relation to age, noise exposures, and other risk factors.

The cohort included in this analysis includes some potential biases as a result of voluntary participation by both apprentices and students, and by exclusion of subjects for evidence of middle ear abnormalities and low frequency hearing loss. While these selection criteria may make the cohort not fully representative of all construction workers and graduate student young adults, there is no reason to suspect that these selections would bias the relations between the measured risk factors and hearing.

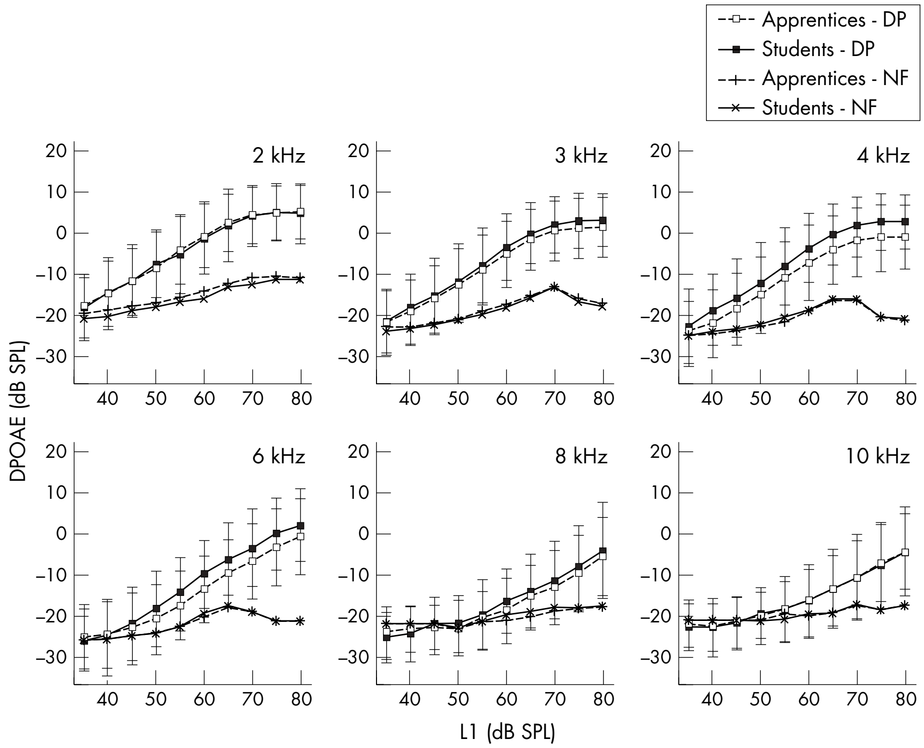

Figure 3 Distortion product otoacoustic emissions I/O growth curves at 2, 3, 4, 6, 8, and 10 kHz by exposure group. Error bars represent ±1 standard deviation.

Table 5 Development of linear mixed models for 4 kHz audiometric threshold†

	Model			
	1 Primary covariates	2 Including covariates with p<0.2	3 Redefined covariates and outliers	4 Selected model
AIC	6513	6505	6439	6475
Intercept	−7.68 (3.07)**	−6.93 (3.06)**	3.35 (2.40)	2.63 (2.32)
Age (years)	0.39 (0.10)***	0.41 (0.11)***		
Age group (baseline <20)				
Age 20–<30			−0.006 (1.95)	−0.003 (1.98)
Age 30–<40			2.33 (2.31)	1.81 (2.23)
Age ⩾40			12.84 (3.41)***	14.06 (2.89)***
Gender (male)	7.56 (1.47)***	6.46 (1.47)***	5.69 (1.45)***	6.08 (1.44)***
Dominant ear	−0.85 (0.59)	−0.89 (0.59)	−0.85 (0.59)	
Family history	1.82 (1.29)	1.44 (1.27)	1.69 (1.25)	
Race (non-white)			−1.94 (1.29)	
Disease history (yes)		−2.83 (1.30)**	−2.34 (1.30)*	
Construction years	0.54 (0.19)***	0.51 (0.19)**	0.66 (0.21)***	0.73 (0.20)***
Non-construction years	0.17 (0.11)	0.06 (0.11)	0.0 (0.1)	
Military machine use (years)		0.75 (0.32)**		
Military machine use (yes)			1.44 (1.95)	
Non-military machine (years)		0.30 (0.23)		
Non-military machine (yes)			2.02 (2.35)	
Firearms use (years)		0.13 (0.13)		
Firearms use (yes)			1.96 (1.42)	2.66 (1.39)*
Motorcycle use (years)		0.21 (0.13)		
Motorcycle use (yes)			1.40 (1.27)	
Power tool use (hours/week)		0.14 (0.15)	0.07 (0.17)	
Paint exposure (years)		−0.86 (0.41)**	−0.86 (0.40)**	−0.86 (0.40)**
Solvent exposure (years)		0.38 (0.18)**	0.45 (0.18)**	0.56 (0.17)**
Subject A			−27.7 (13.3)**	−32.7 (13.2)**
Subject B			35.3 (10.1)***	
Subject C			24.8 (13.4)*	
Subject D			13.2 (13.8)	

†Mixed models including random intercept for subject.
*p<0.1; **p<0.05; ***p<0.01.

Table 6 Reduced linear mixed models for audiometric thresholds (coefficient, (SE), p value)*

	2 kHz	4 kHz	6 kHz	8 kHz
AIC	5690	6475	6593	6567
Intercept	6.56 (±1.17) <0.001	2.63 (2.32) 0.25	7.03 (2.65) 0.008	8.20 (1.95) <0.001
Age (baseline: <20 years)				
20–<30	1.03 (±1.24) >0.2	−0.003 (1.98) 0.999	3.48 (2.19) 0.112	0.39 (2.03) >0.2
30–<40	2.29 (1.38) 0.098	1.81 (2.23) >0.2	6.82 (2.46) 0.006	3.24 (2.27) 0.155
>40	7.27 (1.79 <0.001	14.06 (2.89) <0.001	15.46 (3.22) <0.001	8.07 (2.94) 0.006
Construction years	–	0.73 (0.20) <0.001	0.67 (0.22) 0.002	0.51 (0.20) 0.012
Gender (male)	–	6.08 (1.44) <0.001	4.76 (1.63) 0.004	–
Dominant ear	−1.69 (0.37) <0.001	–	−1.50 (0.62) 0.016	−1.20 (0.67) 0.060
Use firearms regularly	–	2.66 (1.39) 0.056	–	–
Painting (years)	–	−0.86 (0.40) 0.034	–	–
Solvent exposure (years)	–	0.56 (0.17) 0.001	–	–
Family history	–	–	2.82 (1.41) 0.046	–
Motorcycle use	–	–	2.79 (1.34) 0.038	–

*Mixed models including random intercept for subject and adjusted for selected individual outliers (see text).

The way in which we have conducted the modelling does have certain drawbacks. A large number of individual risk factors were included and selected according to a set protocol, rather than using only a small number of pre-selected variables. Reports of past use of five potentially ototoxic drugs were reduced to a single variable (ototoxic therapy), and a list of 14 diseases with known potential to affect hearing were reduced to a single variable (previous disease), because the frequency of each of the individual agents or diseases was very low in the population. Even with this grouping of risk factors, modelling proceeded with 15 independent variables. Given the large number of risk factors included in the initial models, risk factors that may individually have significant effects on hearing could have been dropped from the model because their effect was diluted in the context of the whole study population and large number of covariates.

The accuracy of the results is further limited by the methods used to assess risk factors. As a baseline survey, the risk factors, including noise exposure history, were

Table 7 Reduced linear mixed models for DPOAEs (coefficient, (SE), p value)*

	f2 frequency			
	2014 Hz	3936 Hz	6279 Hz	7965 Hz
AIC	5369	5601	5832	5853
Intercept	6.40 (1.29) <0.001	5.98 (1.48) <0.001	−2.77 (1.61) 0.085	−10.72 (1.45) <0.001
Age (baseline: <20 years)				
20–<30	−0.42 (1.07) >0.2	−1.47 (1.26) >0.2	−0.03 (1.35 >0.2	−0.35 (1.23) >0.2
30–<40	−2.67 (1.20) 0.026	−3.49 (1.41) 0.014	−3.09 (1.52) 0.04	−2.34 (1.37) 0.081
>40	−3.65 (1.59) 0.022	−8.44 (1.88) <0.001	−7.51 (2.02) <0.001	−5.65 (1.83) 0.002
Construction years	–	−0.22 (0.13) 0.080	−0.36 (0.14) 0.009	−0.23 (0.12) 0.064
Gender (male)	−1.94 (0.81) 0.017	−6.01 (0.94) <0.001	−4.40 (1.12) <0.001	−1.63 (0.93) 0.080
Dominant ear	0.62 (0.29) 0.033	–	0.81 (0.40) 0.045	–
Use firearms regularly	−1.94 (0.74) 0.009	–	–	–
Painting (years)	0.47 (0.21) 0.023	–	–	0.41 (0.23) 0.073
Solvent exposure (years)	−0.24 (0.09) 0.011	−0.25 (0.11) 0.019	–	–
Power tool use (years)	–	–	−0.20 (0.11) 0.063	–
Non-white	1.92 (0.71) 0.007	–	–	–
Motorcycle use	–	–	–	−1.38 (0.74) 0.064

*Mixed models including random intercept for subject and adjusted for selected individual outliers (see text).

necessarily limited to self reports on a questionnaire. Although job and exposure history questionnaires are well validated approaches for many occupational exposures, use of a questionnaire to elicit noise exposure history is not well established. Construction workers are able to recall with relatively good accuracy jobs and tasks they have had over the past six months.[30] Nevertheless, without accurate exposure data, the prediction of actual exposure levels would be very crude. Use of years of exposure without regard to level of exposure likely introduces less misclassification than deriving estimated exposure levels from the questionnaire data. Crude indicators for non-occupational exposures were also used, given the large range of exposure levels reported for many non-occupational activities.[31]

The average full shift exposure level among workers employed in a number of the trades participating in the current study is nearly 90 dBA.[18 20] The magnitude of NIHL at 4 kHz estimated in our model, 7 dB over 10 years of exposure, is somewhat less than the 12 dB predicted by the American National Standards Institute (ANSI) model[32] for 10 years of exposure at 90 dB after adjusting for aging. This difference is not surprising for a number of reasons. First, the exposure metric presented here is very crudely measured. Apprentices at the beginning of their training may have somewhat lower exposures than 90 dB as an average, given the intermittency of work and the possibility that training activities may be associated with lower noise levels than onsite work activities. Second, while the ANSI models are based on older, chronically exposed populations, subjects in the current study were relatively young and had few years of noisy work exposure. Poorly characterised interactions between age and noise exposure make comparisons between these groups difficult. In addition, the ANSI models incorporate only age and gender as cofactors, while the models presented here included a variety of other risk factors, thus dispersing the NIHL among several variables.

In conclusion, this analysis supports the general observation that work related exposures to noise continue to play a major role in damaging hearing ability. This appears particularly true in the construction industry where the noise levels remain very high, existence of effective hearing conservation programmes is rare, and the use of hearing protection devices (HPDs) remains far from adequate. Prevention strategies including reducing tool and machine noise, and training and support for effective HPD use are urgently needed in the industry. Direct training with construction apprentices who are just entering the industry may be a key point of entry for changing some of these practices.

In addition, this analysis shows a relatively good correspondence between the associations of noise exposures and other risk factors with DPOAEs and the associations observed with pure tone audiometric thresholds in a young adult working population. A small but significant effect, on both hearing thresholds and otoacoustic emissions, of work in the construction industry was observed in this population in the presence of numerous other potential exposures and personal risk factors. The degree to which DPOAEs can be used to identify persons at risk of hearing damage before the losses become clinically evident, will require careful longitudinal study in a well characterised population.

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REFERENCES

1 **Berger E**. Noise control and hearing conservation: why do it? In: Berger E, *et al*, eds, *The noise manual*. Fairfax, VA: American Industrial Hygiene Association, 2000.
2 **ISO**. *Acoustics—determination of occupational noise exposure and estimation of noise—induced hearing impairment*. Geneva, Switzerland: International Organisation for Standardisation, 1990.
3 **Phaneuf R**, Hetu R. An epidemiological perspective of the causes of hearing loss among industrial workers. *J Otolaryngol* 1990;**19**:31–40.
4 **Henderson D**, Subramaniam M, Boettcher F. Individual susceptibility to noise-induced hearing loss: an old topic revisited. *Ear and Hearing* 1993;**14**:152–68.
5 **Dixon Ward W**. Endogenous factors related to susceptibility to damage from noise. *Occup Med* 1995;**10**:561–75.
6 **Burns W**, Robinson D. *Hearing and noise in industry*. London: HMSO, 1970:241.
7 **Taylor W**, Pearson J, Mair A, *et al*. Study of noise and hearing in jute weaving. *J Acoust Soc Am* 1965;**38**:113–20.
8 **Kemp D**. Otoacoustic emissions, their origin in cochlear function, and use. *Br Med Bull* 2002;**63**:223–41.
9 **Sallustio V**, Portalatini P, Soeo L, *et al*. Auditory dysfunction in occupational noise exposed workers. *Scand Audiol* 1998;**27**:95–110.
10 **Desai A**, Reed D, Cheyne A, *et al*. Absence of otoacoustic emissions in subjects with normal audiometric thresholds implies exposure to noise. *Noise Health* 1999;**1**:58–65.
11 **Attias J**, Furst M, Furman V, *et al*. Noise-induced otoacoustic emission loss with or without hearing loss. *Ear Hear* 1995;**16**:612–18.
12 **Attias J**, Horovitz G, El-Hatib N, *et al*. Detection and clinical diagnosis of noise-induced hearing loss by otoacoustic emissions. *Noise Health* 2001;**3**:19–31.
13 **Prasher D**, Sulkowski W. The role of otoacoustic emissions in screening and evaluation of noise damage. *Int J Occup Med Environ Health* 1999;**12**:183–92.
14 **Hall A**, Lutman M. Methods for early identification of noise-induced hearing loss. *Audiology* 1999;**38**:277–80.
14a **Brown AM**, Kemp DT. Suppressibility of the 2f1–f2 stimulated acoustic emissions in gerbil and man. *Hear Res* 1984;**13**:29–37.
15 **OSHA**. Occupational Noise Exposure: Hearing Conservation Amendment; Final Rule. In: *Fed Reg*. Washington, DC: US Department of Labor, Occupational Safety and Health Administration, 1983:9738–85.
16 **NHCA**. *A practical guide to mobile hearing testing and selecting a service provider (Guide #3)*. Denver, CO: National Hearing Conservation Association, 1996.
17 **McBride D**, Williams S. Audiometric notch as a sign of noise induced hearing loss. *Occup Environ Med* 2001;**58**:46–51.
18 **Neitzel R**, Seixas N, Camp J, *et al*. An assessment of occupational noise exposures in four construction trades. *Am Ind Hyg Assoc J* 1999;**60**:807–17.
19 **Suter A**. Construction noise: exposure, effects and the potential for remediation; a review and analysis. *Am Indus Hyg Assoc J* 2002;**63**:768–89.
20 **Seixas N**, Ren K, Neitzel R, *et al*. Noise exposure among construction electricians. *Am Indus Hyg Assoc J* 2001;**62**:615–21.
21 **Clark WW**. Noise exposure from leisure activities: a review. *J Acoust Soc Am* 1991;**90**:175–81.
22 **Johnson DL**, Riffle C. Effects of gunfire on hearing level for selected individuals of the Inter-Industry Noise Study. *J Acoust Soc Am* 1982;**72**:1311–14.
23 **Stewart M**, Konkle DF, Simpson TH. The effect of recreational gunfire noise on hearing in workers exposed to occupational noise. *Ear Nose Throat J* 2001;**80**:32–40.
24 **Nondahl DM**, Cruickshanks KJ, Wiley TL, *et al*. Recreational firearm use and hearing loss. *Arch Fam Med* 2000;**9**:352–7.
25 **Dalton S**, Cruickshanks KWT, *et al*. Association of leisure-time noise exposure and hearing loss. *Audiology* 2001;**40**:1–9.
26 **Franks JR**, Davis RR, Kreig EF Jr. Analysis of a hearing conservation program data base: factors other than workplace noise. *Ear Hear* 1989;**10**:273–80.
27 **Johnson A**, Nylen P. Effects of industrial solvents on hearing. *Occupational Medicine: State of the Art Reviews* 1995;**10**:623–40.
28 **Sliwinska-Kowalska M**, Zamyslowska-Szmytke E, Szymczak W, *et al*. Ototoxic effects of occupational exposure to styrene and co-exposure to styrene and noise. *J Occup Environ Med* 2003;**45**:15–24.
29 **Zhao F**, Stephens D. Test-retest variability of distortion product otoacoustic emissions in human ears with normal hearing. *Scand Audiol* 1999;**28**:171–8.
30 **Reeb-Whitaker C**, Seixas N, Sheppard L, *et al*. Accuracy of task recall for epidemiological exposure assessment to construction noise. *Occup Environ Med* 2004;**61**:135–42.
31 **Neitzel R**, Seixas N, Olson J, *et al*. Non-occupational noise: exposures associated with routine activities. *J Acoust Soc Am* 2004;**115**:237–45.
32 **ANSI**. *Determination of occupational noise exposure and estimation of noise-induced hearing impairment*. New York, NY: American National Standards Institute, Inc., 1996.