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Effects of Concurrent Noise and Jet Fuel Exposure on Hearing Loss

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Learning Objectives

- Recall the criteria met by workers at a military installation who were enrolled in this study, and the estimated level and duration of exposure to both noise and jet fuel.
- Infer from the study findings whether—and to what extent—exposure to both noise and jet fuel impairs hearing more than exposure to noise alone.
- Define the conditions under which workers exposed to fuel and solvents should be offered measures for conserving hearing.

Objectives: *We sought to examine the effects of occupational exposure to jet fuel on hearing in military workers.* ***Methods:*** *Noise-exposed subjects, with or without jet fuel exposure, underwent hearing tests. Work histories, recreational exposures, protective equipment, medical histories, alcohol, smoking, and demographics were collected by questionnaire. Jet fuel, solvent, and noise exposure data were collected from records. Fuel exposure estimates were less than 34% of the OSHA Threshold Limit Values.* ***Results:*** *Subjects with 3 years of jet fuel exposure had a 70% increase in adjusted odds of hearing loss (OR = 1.7; 95% CI = 1.14–2.53) and the odds increased to 2.41 (95% CI = 1.04–5.57) for 12 years of noise and fuel exposure.* ***Conclusions:*** *These findings suggest that jet fuel has a toxic affect on the auditory system.* (J Occup Environ Med. *2005;47: 212–218*)

In 1984, Barregård and Axelsson[1] were the first to suggest that solvents as well as noise contributed to occupational hearing loss (OHL). In 1998, revised U.S. Army guidelines[2] required consideration of ototoxic chemical exposures, as well as traditional noise exposure, for workers' inclusion in a hearing-conservation program. Laboratory animal and occupational studies have demonstrated that organic solvents, such as toluene, contribute to OHL and exacerbate damage from noise exposure.[3–7] Because noise can damage various parts of the cochlea, the potential for overlap with neurotoxic solvents' site-specific actions is high. The damage may progress after the exposure is stopped or may be reversible.[8–15] Morata reviewed the effects of combined exposures to solvents and noise on hearing.[16]

Exposure to single chemicals is rare in most work places; hence, understanding the possible effects of combined exposures or complex mixtures is vital.[17] In a study of more than 3284 Danish men in various industries, Jacobsen et al[18] found a small additive effect in workers exposed to noise and solvents. Morata et al[19] found greater hearing loss among printers exposed to noise and toluene or mixed solvents than noise alone. Animal studies have demonstrated greater hearing loss from exposures to solvent mixtures containing toluene, xylene, n-heptane, and styrene in several combinations than was found in single-solvent exposures.[15,20,21]

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Ödkvist et al[22] found hearing and central nervous system deficits in workers exposed to jet fuel and solvents despite low exposures. Jet fuels have potential ototoxic components, including *n*-hexane, *n*-heptane, toluene, and xylene[3,9,15,19,20,23]; the ototoxicity of these compounds has been reviewed by Johnson and Nylén and Fechter.[24,25] These solvents also are components of degreasing/cleaning agents, paints, adhesives, and plastics.[17]

This study examined whether fuels, composed of a complex mixture of organic solvents, increase the hearing loss in noise-exposed workers compared with those with only noise exposure. The study examined workers exposed primarily to the jet fuel JP-4 at one military installation. JP-4 is a mixture of short- and long-chain hydrocarbons and alkanes containing known ototoxins.[26]

Materials and Methods

The association between hearing and jet fuel exposure was assessed by a study of current workers at one military installation using historically collected information that characterized both solvent and noise exposure. Subjects were aircraft maintenance personnel and other workers, all of whom were required to have a minimum of 3 years of occupational noise exposure (85 dBA or greater). Fuel-exposed subjects also were required to have a minimum of 3 years jet fuel exposure.[18,19] Subjects were recruited using small group presentations to 330 workers who had routine exposure to noise; 276 (84%) agreed to participate. An audiologist unaware of subjects' exposure status reviewed the medical records of all potential subjects whose baseline audiogram demonstrated a hearing loss of greater than 25 dB at 1–4 kHz or 35 dB at 6 kHz.[27] Those potential subjects with conditions that could mask exposure or noise effects were excluded. Detailed explanations for ineligibility are in Table 1. Thus, of the 276, 138 (50%) met eligibility requirements and were recruited into the study.

Data were collected through self-administered questionnaires covering demographics, military history, medical history, present health, occupational and nonoccupational noise exposures, alcohol consumption, and tobacco use. The medical history included data on medications, injuries, surgery, diabetes, high blood pressure, measles, mumps, ear infections, and tinnitus. Diabetes and high blood pressure were considered positive if the worker had received treatment at any time.

Exposure Assessment: Fuels

Personnel at this military installation are categorized by occupational exposures and work sites or by using a classification system referred to as Potential Exposure Groups (PEGs). PEGs were used initially to identify study subjects. Information on noise dosimetry and solvent air sampling (benzene, toluene, xylene, hexane, heptane, jet fuel), including collection time, results, and task descriptions, was collected for all subjects' PEGs. Data sources included historical shop industrial hygiene records, current USAF industrial hygiene database records, industrial hygienists, workers, and supervisors.

Each subject was assigned two jet fuel-exposure variables. The first variable was the number of years (duration) they worked in fuel-exposed PEGs. Any PEG having individual hygiene information of jet fuel use or air sampling data was considered "exposed." The second fuel exposure variable was based on cumulative career estimates of jet fuel exposure measured in milligrams/cubic meter (mg/m^3). Quantitative estimates of jet fuel exposure were based on personal air samples of JP-4 with task descriptions. JP-8, which replaced JP-4, was not used for exposure estimates because the military installation switched fuels less than 2 years before the study began, providing insufficient duration of exposure. These air samples were used to generate annual JP-4 estimates for each exposed PEG as follows:

$$\text{Annual estimate} = \text{average sampling for task} \times \text{task frequency}$$

Where task frequency = number of times a worker performed the task annually.

$$\text{Subjects' cumulative exposure} = \Sigma\,(\text{PEG annual estimate} \times \text{duration in PEG})$$

Before calculating task averages, samples were sorted as above or below detectable levels (BDLs). Where it was possible, the flow rates, collection times, and laboratory detection levels were used to calculate a minimum detection limit (DL) as follows:

$$\text{DL} = (\text{reported laboratory DL})/(\text{volume air}),$$

where volume air = time × flow rate.

TABLE 1
Reasons for Ineligibility by Current Exposure Status

Reason	Exposed	Unexposed	Total
Insufficient audiograms	0	18	18
Insufficient exposure (noise or fuel)	1	20	21
On leave	1	4	5
Other exposures, including ethanol >2 drinks/day	4	3	7
Medical conditions*	17	25	42
Hearing loss†	25	20	45
Total	48	90	138

*Injury, diabetes, hypertension, medications.
†Hearing loss at baseline audiogram considered too great to demonstrate measurable changes after exposures.

When no laboratory detection limit could be found, the lowest result from the same or closest year was used to avoid overestimating exposure. Finally, data considered as BDLs were set to the DL divided by the square root of two according to Hornung and Reed.[28] When an exposed PEG had no air sampling data, subjects' exposures were calculated from a similar PEG, identified from PEG titles, PEG descriptions, and interviews with military installation personnel.

Subjects were assigned to 186 PEGs during the course of their occupational histories. Of these PEGs, 39 had definitive jet fuel exposure (630 person-years), 9 had potential for exposure (325 person-years), and 138 were considered unexposed (1048 person-years). Those PEGs with certain or potential exposure were considered "exposed" for the duration exposure estimates. Thirty-four (71%) of the jet fuel-exposed PEGs had air sampling data with task descriptions that could be used to determine annual exposure estimates (as described above). Annual PEG exposure estimates fell into three distinct groups: 0.1 to 4400 mg/m^3 (accounting for 20 PEGs and 516 person-years); 10,800 to 14,600 mg/m^3 (7 PEGs, 95 person-years); 19,500 to 53,900 mg/m^3 (7 PEGs, 302 person-years) with an overall SD of 963 mg/m^3. Five jet fuel-exposed PEGs did not contribute to the cumulative exposure estimates because of lack of information to assign a similar PEG's estimate (42-person years).

Exposure Assessment: Noise

The military noise dosimetry is normalized to an 8-hour shift. Resulting values are expressed as equivalent continuous level (ECL). ECL is similar to a TWA for noise; however, it refers specifically to three dB exchange rate and implies equal energy A-weighting (dBA).[29] For this study, ECLs were grouped and ranked and entered as one to four (<85, 85 to 89.99, 90 to 94.99, >95 dBA). The five dB range was necessary because the tolerances for noise dosimetry equipment for 2000 and 2500 HZ are ± 2.5 dB or less at lower frequencies.[30]

Noise dosimetry (ranks) were combined by PEG and a summary score (A to F) given. Most recent noise dosimetry estimates were based on a three dBA exchange rate, which is a more conservative estimate of noise than the decades-old four dBA exchange rate that the military used until 1993. Different exchange rates did not change the daily dosimetry ranking. Ranks at three dB and four dB were separated, and each PEG was given its noise score based on both the four dBA and three dBA. Scores were so similar that these were combined.

This scoring system assumes that sound less than 85 dBA is not ototraumatics whereas noise greater than 95 dBA is ototraumatic and that there may be differences between consistent levels of sound and sound with peaks of greater intensity. It differentiates among those jobs with consistent and intermittent noise. Final scores were used to assign no noise (score = A, dosimetry ranks 1 and 2 only) and noise (score = B to F, dosimetry includes ranks 3 to 5) designations to each PEG. Workers' noise exposure was calculated by summing total duration in PEGs categorized as "noise." All subjects had at least 3 years employment in PEGs scored B to F, including their current PEG, but had not necessarily worked continuously in noise-exposed PEGs.

Hearing Testing

Otoscopy, pure-tone audiometry, and immittance audiometry were performed to assess the status of subjects' current hearing. Hearing tests were administered using the USAF Hearing Evaluation Automated Registry System (HEARS) and GSI-61 Clinical Audiometers (Grason-Stadler Inc.). HEARS is a military-wide, automated system for testing pure tone audiometry used for annual hearing tests. It checks hearing acuity at 500, 1000, 2000, 3000, 4000, and 6000 Hz. The GSI-33 clinical middle-ear analyzer was used to test reflexes and impedance on all subjects.

Baseline audiograms were collected from subjects' medical files by the audiologist. Baseline audiograms were performed by certified technicians (29 CFR 1910.95) at hiring or when workers began in noisy jobs. The audiologist chose the earliest dependable audiogram, considering factors such as patterns of hearing loss and type of equipment used. The audiologist was unaware of whether subjects were ever exposed to jet fuel.

When subjects were exposed to noise, they were included in the hearing conservation program and received annual hearing tests. Current audiograms, by a certified technician and available in the medical records, were used for subjects who had an examination within 3 months of the study testing (n = 35). All subjects without a current audiogram were tested by the same certified technician or audiologist. All subjects underwent a visual examination and immittance audiometry to confirm structural integrity of the eardrum and nervous system.

Hearing loss (HL) was defined as at least 15-dB change from baseline in at least one ear at 1 to 4 kHz. Persistent hearing loss (PHL) was defined as at least 15-dB change from baseline during two successive years in the same ear at the same frequency at 1 to 4 kHz. This definition of PHL reduces the likelihood of a temporary threshold shift being misclassified as a permanent hearing loss.[31]

Statistical Analysis

Data were checked for duplicate entries, invalid codes, and out-of-range values. Then clean files were imported into the Statistical Analysis System (SAS) 6.12 for Macintosh. Logistic regression was performed using HL and PHL as dependent variables. Significant ($P \leq 0.25$) covariates were selected for inclusion after univariate analyses. Models including interactions were reduced using backwards elimination using an alpha-level of 0.10. Odds ratios were estimated based on the final logistic models. The analyses were performed using both the qualitative and quantitative exposure estimates.

Seventeen possible covariates were tested individually for inclusion in the full model using an alpha-level of 0.25; the following seven were retained: age (years); tinnitus (yes/no); drank alcohol regularly (yes/no for at least one beer, glass of wine or mixed drink per month); exposed to loud noise in the military (years); longest duration of noise-hazardous leisure activity (years); hearing protection worn during noisy leisure activities (yes/no); and cigarettes smoked (pack-years). Five interaction terms were included in the full model: noise and smoking, jet fuel and smoking, jet fuel and alcohol, hearing protection and smoking, jet fuel and noise. The full model, including the jet fuel and noise duration exposure variables, was reduced using backwards elimination of the insignificant variables in the logistic regression model, applying an alpha level of 0.10. The reduced model was confirmed by a forward inclusion strategy.

Results

Exposed workers were recruited from sheet metal (n = 41) and fuel systems (n = 29) job tasks where there is regular exposure to jet fuel or residual fuel. Unexposed workers were recruited from job tasks without fuel exposure such as civil engineering (n = 4), plumbers/electricians/utilities (n = 38), parts preparation (n = 12), heat shop operators (n = 10), and other (n = 4). After accounting for the subjects' complete work histories, 20 subjects originally identified as nonexposed had 6 months or more exposure to jet fuel in their previous jobs and 48 never had fuel exposure in any job (Table 2). All subjects were high school graduates with additional schooling in their trades. The groups differed little in age, use of firearms for leisure, proportion of smokers or alcohol drinkers. There were 5 active duty personnel in the exposed group and 19 in the unexposed group. There were two women and two blacks in the exposed group but none in the unexposed group.

Table 3 presents the results of the final logistic regression model with the odds ratio for developing a HL or PHL. Cumulative jet fuel exposure (employment exposure in mg/m^3) level was not statistically significant in HL or PHL models. The duration of jet fuel exposure was not significant in the HL main effects or interactions models. Post-hoc analysis of hearing loss in one or both ears, left ears, and right ears also was not statistically significant. Age (OR = 1.17; 95% CI = 1.08–1.25) and military noise exposure (yes/no) (OR = 1.12; 95% CI = 1.01–1.24) were significant.

The duration of jet fuel exposure was significant; however, in the PHL model with an odds ratio of 1.23 (95% CI = 1.05–1.44; Table 3). Age that the subject began drinking was the most significant factor, representing a 3-fold increase in risk (OR 3.03; 95% CI = 1.42–6.45). Tinnitus also was a significant covariate (OR 2.34; 95% CI = 1.09–5.01).

TABLE 2
Characterization of Subjects by Exposed and Unexposed Groups

	Exposed (n = 90)	Unexposed (n = 48)
	Mean (SD) (range) or % of Group	Mean (SD) (range) or % of Group
Variable		
Age	42.8 (6.0) (22.5–57)	40.8 (9.9) (22.5–59.5)
Civilian	94%	50%
Years worked	15.8 (5.4) (2.75–30.5)	15.6 (7.2) (2.75–30.6)
Years of jet fuel exposure	10.6 (6.83) (0.5–29.7)	0
Years of noise exposure	13.4 (5.3) (3–29.7)	11.0 (7.7) (3–30.6)
Age started to drink regularly	19.6 (13–37)	18.5 (12–31)
Percent who drank	63%	66%
Smoking, pack-years	20.7 (15.5) (1.5–74.3)	13.4 (16) (0.5–71.8)
Percent who smoked	44%	45%
Years of leisure use of firearms	18.2 (11.4) (0.5–40)	14.2 (13.4) (0.5–40)
Percent have leisure use of firearms	55%	47%

TABLE 3
Results of Hearing Loss and Persistent Hearing Loss Logistic Regression With Jet Fuel by Noise Interaction

Variable	Adjusted Odds Ratio	95% CI
Hearing loss		
Age	1.17	1.08–1.25
Jet fuel duration	1.13	0.96–1.33
Noise duration	1.12	1.01–1.24
Jet fuel by noise	0.99	0.98–1.00
Hearing protection	0.81	0.63–1.03
Persistent hearing loss		
Age	1.14	1.07–1.21
Jet fuel duration	1.23	1.05–1.44
Noise duration	1.10	1.02–1.19
Jet fuel by noise	0.99	0.98–1.00
Ever drank alcohol regularly	3.03	1.42–6.45
Tinnitus	2.34	1.09–5.01

This PHL model was examined further by applying different exposure conditions. First, when jet fuel and noise exposure duration increase equally, jet fuel exposure was statistically significant for the first 3 through 12 years only, OR = 1.70 (95% CI = 1.14–2.3) to 2.41 (95% CI = 1.04–5.57). Next, under the condition of only minimal duration of noise exposure (3 years), the odds ratio of hearing loss due to jet fuel exposure was 8.25 at 12 years (95% CI = 1.67–55.6) and continued to be significant as the number of years of fuel exposure increased. Third, jet fuel exposure was not significant in the model for PHL without the jet fuel and noise interaction (OR 1.01; 95% CI = 0.96–1.06).

Because age is correlated with both long duration and cumulative jet fuel exposure as well as increased risk of hearing loss, the model was re-examined. The model was tested with age as a dichotomous variable either above (coded 1) or below (coded 0) the median of 42 years. The odds ratio for the dichotomized age variable in the PHL model increased to 7.5 (P value = 0.0001; 95% CI = 3.35–16.9), while jet fuel became even stronger as a predictor of HL OR = 1.89 (95% CI = 1.24–2.89). Noise was statistically significant in all the models tested for HL and PHL, consistent with the general understanding of noise-induced hearing loss (NIHL).

Discussion

Annual cumulative exposure estimates based on the Threshold Limit Value/Permissible Exposure Limit (TLV/PEL) of 700 mg/m^3 for JP-4 and 350 mg/m^3 for JP-8 would result in a maximum exposure of 161,000 mg/m^3 per year and 80,500 mg/m^3 per year, respectively. Cumulative annual JP-4 exposures calculated for this study ranged from 0 to 33% of this maximum for JP-4 and 0.5 to 11% for JP-8. Other studies at U.S. military installations also have found exposures well below the TLV and are consistent with this study's estimates.[32,33]

Duration of jet fuel exposure increased the odds of persistent hearing loss even though the estimated exposures were well be TLV and PEL. These results are consistent with an increasing body of research that suggests that organic solvents are ototoxic below exposure limits.[6] Morioka et al[34] found increased prevalence of poorer hearing thresholds in workers exposed to organic solvents. Sliwinska-Kowalska et al[35] found significantly increased relative risks (RR) of hearing loss in the solvent-only exposure groups.

Jet fuel exposure increases the adjusted odds of a 15 dB or greater PHL when combined with noise exposure during the first 12 years of exposure. Odds increased 70% at 3 years exposure to 140% at 12 years (OR = 2.41). The effects of jet fuel exposure were statistically insignificant with more than 12 years of combined noise and jet fuel exposure. Other studies of occupational solvent exposure have demonstrated measurable hearing loss sooner than is usually seen with noise exposure alone (3[18] to 5[16,18] years of exposure). The period of latency before persistent loss appears to be dependent on the ototoxin and the characteristics of the exposure, and needs further exploration. The fact that the risks for jet fuel did not continue after 13 years of exposure suggests a plateauing effect and/or that the noise-induced hearing loss may become more important than the solvent induced hearing loss for those continuing to have exposure to both. It is possible that fuels may continue to damage hearing, but not in a manner measured in this study.

As expected, noise, tinnitus, and age were significant in the final PHL model. Noise is the most common ototraumatic exposure in the workplace. Effects of age on hearing are well documented. Tinnitus has been associated with noise exposure and chemical exposure[36] and is a sign of improper cochlear function. The interaction of noise and jet fuel is supported by the potential overlap in sites of action for solvent and noise ototoxicity: a potential increased by the wide range of solvents contained in jet fuel. The combined effect may differ from that of individual agents.[6] Studies continue to support increased effects from the combination of noise and solvents.[34,37]

It is well established that organic solvents are ototoxic in the rat, but the ototoxic mechanism is not fully understood. Moreover, the intoxication route taken to reach the organ of Corti is still uncertain. Loquet et al[38] in 1998 investigated the distribution of toluene, finding that the cerebrospinal and inner ear fluids were free from detectable solvents, whereas the organ of Corti, the nerves and the brain were contaminated. Therefore, toluene-induced hearing losses may be caused by tissue intoxication rather than by fluid contamination.

In humans, solvents are known to affect peripheral and central nervous systems. Some solvents might have a cochlear and a retrocochlear effect. Noise, for example, might alter the distribution of agents to the cochlea by altering cochlear blood flow or metabolic substrate utilization or it might disrupt the cochlear-blood barrier permitting more of the toxicant to enter the cochlear compartment.[39]

The odds ratio for "ever drank alcohol regularly" was 3.03 (95% CI = 1.42–6.45) with a positive coefficient. Alcohol appears to potentiate the effects of ototoxic solvents[40] and affects the metabolism of jet fuel ingredients.[41,42]

The lack of significance in the HL analysis and jet fuel exposures is not surprising because of the nature of temporary hearing loss and variability in pure tone audiometry. Using PHL reduces the chance that a subject will be misclassified as having a true hearing loss, rather than a temporary threshold shift. Temporary threshold shifts caused by noise exposure are common, for example, after listening to a loud vehicle sound system while driving, and would bias the statistical findings toward the null.

Cumulative jet fuel exposure level was not statistically significant in HL or PHL models when jet fuel was estimated by cumulative exposure. The lack of significance may reflect the inadequacy of the exposure models that required many more assumptions of level of exposures than did models involving the variable "duration of exposure." Some studies of solvent exposure and hearing loss have presented an increased prevalence of hearing loss with solvent exposure (yes/no), rather than a dose response.[22,21] In contrast, Morata et al[7] found the odds ratio for hearing loss was 1.76 times greater for each gram of urinary hippuric acid per gram of creatinine (a toluene dose marker). Sliwinska-Kowalska et al.[37] found the odds ratio for hearing loss was 1.004 for each increment of the index of lifetime exposure to solvents.

This cross-sectional investigation was the first study of potential ototoxicity of jet fuel exposure. A prospective study is imperative to optimally measure latency. Reflex decay testing and contralateral acoustic reflexes should be tested to investigate the location of jet fuel ototoxicity. Morata et al[6,7,19] found significant differences in response in reflex decay in workers exposed to toluene and mixed solvents, suggestive of retrocochlear disorders. This analysis did not distinguish between sensorineural and conductive hearing loss by performing bone conduction studies. Medical history, audiogram review, and tympanometry were used to eliminate conductive losses (mechanical dysfunction) and will identify most people with a conductive hearing loss.

This investigation predominantly examined the effects of JP-4 because JP-8 was introduced to the military installation fewer than 2 years previous to the study. JP-8 contains lower percentages of known ototoxins such as toluene and xylene than JP-4 but evaporates more slowly, creating an increased opportunity for dermal absorption. Overall, it may be less neurotoxic, but a study needs to be performed after JP-8 has been in use for a greater period of time.

In summary, exposure estimates in aircraft maintenance workers were well below the threshold limit values. Despite the low levels of fuel exposure, statistically significant increases in the probability of a persistent hearing loss were observed in jet fuel exposed subjects. Aircraft maintenance workers, like workers in many other fields, cannot be completely separated from noise or jet fuel, but can be encouraged to wear hearing protection and to reduce their contact with fuel and fuel residues. Also, fuel and solvent exposure should be considered when placing workers in a hearing conservation program, even in those cases when noise levels may be lower than 85 dB.[35,42]

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