

Impulse noise and hand-arm vibration in relation to sensory neural hearing loss

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STARCK J, PEKKARINEN J, PYYKKÖ I. Impulse noise and hand-arm vibration in relation to sensory neural hearing loss. *Scand J Work Environ Health* 14 (1988) 265–271. The present study was carried out to determine whether impulse noise and simultaneous exposure to noise and vibration can aggravate sensory neural hearing loss (SNHL) among forest (N = 199) and shipyard (N = 171) workers. The average level of exposure to noise outside the used earmuffs and the average exposure over time were nearly equal for the two groups. The impulsiveness of the noise and the average exposure level inside the earmuffs were measured with a miniature microphone. The hearing threshold of the workers was measured at 4 kHz and then estimated according to Robinson's model to compare the observed and expected hearing loss. The impulsiveness of the noise was greater both outside and inside the earmuffs in shipyard work than in forest work. The average SNHL was higher than predicted for the shipyard workers and about the same as predicted for the forest workers. The total exposure level inside the earmuffs was influenced by the total wearing time. The low frequencies of the chain-saw noise were not attenuated sufficiently by the earmuffs to protect the workers' hearing. The present study suggests that exposure to impulse noise increases the risk of SNHL, but that simultaneous exposure to hand-arm vibration and noise does not.

Key terms: attenuation, earmuffs, forest work, impulsiveness, noise effects, noise exposure, permanent hearing loss, shipyard work.

The damaging effects of noise on hearing are considered to be dependent on the energy content of noise so that equal energy causes equal hearing loss. Industrial noise containing sudden sound pressure peak levels may, however, pose an increased risk for noise-induced permanent threshold shift that cannot be predicted from continuous noise with equal energy (8, 9, 28, 35, 50, 51, 53). This possibility has been illustrated in laboratory studies on animals (17, 31, 43), but also contradictory and nonconclusive reports have been presented (3, 9, 16, 19). Moreover, it has been suggested that simultaneous exposure to hand-arm vibration may also aggravate noise-induced permanent threshold shift (20, 30, 33, 41, 42, 52).

Several methods have been proposed for assessing the risk of hearing loss caused by impulse noise exposure (1, 3, 8, 9, 19, 26, 27, 29, 34, 36, 46, 49). In a study on hearing loss caused by shipyard noise (32), the use of hearing protectors was not considered although impulse noise was shown to aggravate hearing loss. Another extensive study on 250 000 workers reported great variation in the use of hearing protectors, but it did not include hearing protector use in the risk analysis (19). Studies on the relation between hearing loss and the impulsiveness of noise inside earmuffs during industrial work could not be found. The present

work was aimed at comparing the measured and predicted hearing levels of workers exposed to noise and vibration generated by hand-held power tools.

Subjects and methods

Subjects

The study was carried out among 199 professional forest workers and 171 platers working at a shipyard. (See table 1 in the results section for the groups' average ages and exposure characteristics). The forest workers were examined during the period 1972–1986 (39, 47), and the shipyard workers were studied in 1986. In the medical examination the hearing thresholds were measured after a 15- to 48-h period free of exposure to occupational noise. Workers with hearing loss caused by ear diseases or accidents were excluded from both groups by otological examination.

Noise and vibration measurements

The noise and vibration of chain saws were measured as pine or spruce logs, supported horizontally on a bench, were cut. The chain saw used for the measurements was a make (Husqvarna 154 G) commonly used by Finnish forest workers (39). The measurements of the pneumatic power tools most commonly used by the platers were made in a shipyard assembly hall during normal work. In contrast to the forest workers, the shipyard workers used several kinds of hand-held power tools, eg, pneumatic hammers, grinding machines, and circular saws, in their work.

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We inquired about the men's work habits in order to estimate their occupational noise and vibration exposure. Both the forest workers and the shipyard workers used safety helmets with earmuffs during work. To determine the noise reaching the inner ear, a miniature microphone (Knowles 1785 LY072) was attached to the middle of the ear canal entrance (4, 36). Outside the earmuff a microphone of the same type was attached to the headband of the earmuff (37). The attenuation of the earmuffs was calculated as the difference between the signals, which is also known as noise reduction (6). These data, and the results from previous studies in a shipyard (36) and in forest work (40), were used to predict individual hearing loss according to a model developed by Robinson (44).

The application forces of the earmuffs used by the forest workers were measured before the noise and vibration measurements with a strain gauge transducer (Kyowa LM-2KA) connected to a computer (13, 14, 22). An accelerometer (Brüel & Kjaer 4375) was attached to the handle of the tool with a mechanical filter (Brüel & Kjaer UA 0559). Another accelerometer (Brüel & Kjaer 4371) was attached to the corresponding wrist of the operator to measure the transmission of vibration from the tool handle (12). The main axes of the accelerometers were parallel to the wrist.

The noise and vibration measurements were made with a digital multichannel sampling unit (Hewlett-Packard 6944) controlled by a microcomputer (Hewlett-Packard 9920). The sampling speed of the analogue-to-digital converter was 25 000 samples/s for each channel (37). The memory was expanded to two megabytes, which enabled 200-ms blocks to be sampled, each block containing 5 000 samples. The A-weighted equivalent level for noise (23) and the frequency-weighted acceleration for vibration (24) were calculated from five to ten time-domain blocks averaged in each measurement in order to minimize the variance (5). For the estimation of vibration transmission, unweighted vibration acceleration was also measured. Impulsiveness was determined as the difference between the peak and root-mean-square (rms) levels of the signal; this value corresponds to the crest factor (9, 19, 26, 27, 36, 48, 49). The crest factor is independent of energy content but describes the shape of the signal (8, 21).

Robinson's model for predicting hearing loss

Robinson's model (44) has the A-weighted equivalent noise level, duration of exposure, and age of the exposed worker as predictor variables. The calculated median hearing level was compared at 4 kHz to the average of the audiometric measurements made from the left and right ears.

Data on occupational history and the use of hearing protectors were used for the calculation of individual exposure. A worker's exposure to noise is generally comprised of several exposure levels and durations,

and the use of hearing protectors varies. The application of Robinson's model is based on the immission level of noise, which was defined for each worker according to equations 1 through 5 as follows:

$$L_{di} = 10 \log [(T_{di}/8) \cdot 10^{L_i/10}], \quad \text{equation 1}$$

where L_{di} = exposure level to noise outside the hearing protector corrected to 8 h of daily worktime in noise, T_{di} = daily duration of the noise exposure level L_i , L_i = A-weighted noise level outside the hearing protector, and $i = 1 \dots n$ work periods ($i = 1$ for the present period and $i > 1$ for earlier periods).

For the shipyard workers, n was ≤ 3 , but for the forest workers $n = 1$ since, in most cases, forestry had been their only occupation. For the present ($i = 1$) work period, L_i noise levels were measured at the workplace. For previous work periods ($i > 1$), the L_i noise levels were estimated from the individual occupational histories and data of earlier studies (36). The effect of the hearing protector on the exposure to noise was calculated as

$$L_{pi} = 10 \log \{ (U_{pi}/100) \cdot 10^{(L_{di}-L_{ai})/10} + [1-(U_{pi}/100)] \cdot 10^{L_{di}/10} \}, \quad \text{equation 2}$$

where L_{pi} = daily exposure to noise including the effect of hearing protectors, U_{pi} = use of hearing protectors as a percentage of the total duration of work in noise, and L_{ai} = measured average attenuation of the hearing protectors.

L_{ai} had a mean attenuation of 17 dB for the shipyard workers ($N = 28$) (36) and 12 dB for the forest workers ($N = 12$) (40). We determined the total exposure level of each worker by summing the daily exposure levels over the exposure periods in years as follows:

$$L_{tot} = 10 \log \sum_{i=1}^n [(T_{yi}/T) \cdot 10^{L_{pi}/10}] \quad \text{equation 3}$$

and

$$L_E = L_{tot} + 10 \log T, \quad \text{equation 4}$$

where L_{tot} = the total exposure level to noise over time in years, T_{yi} = duration of each exposure period i in years, T = total time for noisy occupations in years, and L_E = A-weighted noise immission level.

The A-weighted noise immission level defined for each worker individually was used in Robinson's model to calculate, with 50 % probability, the age-corrected hearing level (HL) at 4 kHz (40, 44) as follows:

$$HL = 27.5 \{ 1 + \tanh [(L_E - 112.5 \text{ dB})/15] + 0.012 (N - 20)^2 \}, \quad \text{equation 5}$$

where N = age (in years) of each worker.

Results

The results of the evaluation of the different exposures of the forest and shipyard workers have been summarized in table 1 in relation to the risk of hearing loss.

Table 1. Summary of the factors related to the evaluation of the risk of hearing loss among the forest and shipyard workers. (SE = standard error of the mean, VWF = vibration-induced white fingers)

	Forest workers (N = 199)				Shipyard workers (N = 171)			
	Mean	SE	Range	% ^a	Mean	SE	Range	% ^a
Age (years)	43.1	0.6	.	.	35.3	0.6	.	.
Noise								
Total exposure level (dB)	94.8	0.3	.	.	86.4	0.4	.	.
Total exposure time (years)	16.0	0.5	.	.	15.1	0.6	.	.
Noise immission level (dB)	106.3	0.4	.	.	97.5	0.5	.	.
Use of earmuffs (%)				79				93
Vibration								
Daily exposure time (h)	5	.	.	.	2	.	.	.
Acceleration (m/s ²)	.	.	1.8–2.2	.	.	.	0.4–6	.
Prevalence of VWF (%)	.	.	.	7	.	.	.	2.9
Hearing threshold level (dB)								
Measured at 4 kHz	26.7	1.4 NS	.	.	21.5	1.4***	.	.
Predicted at 4 kHz	25.2	0.8 NS	.	.	11.8	0.7***	.	.

^a For the use of earmuffs it is the percentage of time earmuffs were used; for the prevalence of VWF it is the percentage of the total number of workers.

*** P < 0.005, NS = not significant.

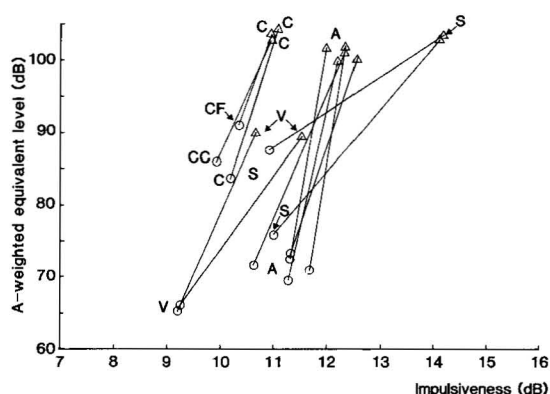


Figure 1. Equivalent levels and impulsiveness of noise from hand-held power tools used by one worker in a shipyard for angle grinding (A), vertical grinding (V), and scaling (S) and from chain saws used by 50 forest workers. (C = chain saw and helmet without liner, CF = chain saw and helmet with fur liner, CC = chain saw and helmet with cloth liner, Δ = outside the earmuff, ○ = inside the earmuff).

Noise

The equivalent noise level and impulsiveness were calculated for the noise outside and inside the earmuffs (figure 1). The equivalent noise level was about 100 dB outside the earmuffs both for the tools used in the shipyard and for the chain saws. The total immission level was calculated from the total exposure time and total exposure level (equation 4). The exposure times were nearly equal, but both the total exposure level and the noise immission level were greater for the forest workers than for the shipyard workers (table 1). The attenuation of the equivalent noise level and the impulsiveness was clearly greater for shipyard noise than for chain-saw noise. At the shipyard, the attenuation varied from 14 to 30 dB for the same worker depending on the tool being used (figure 1). In forest work, the equivalent noise level was below 85 dB when the

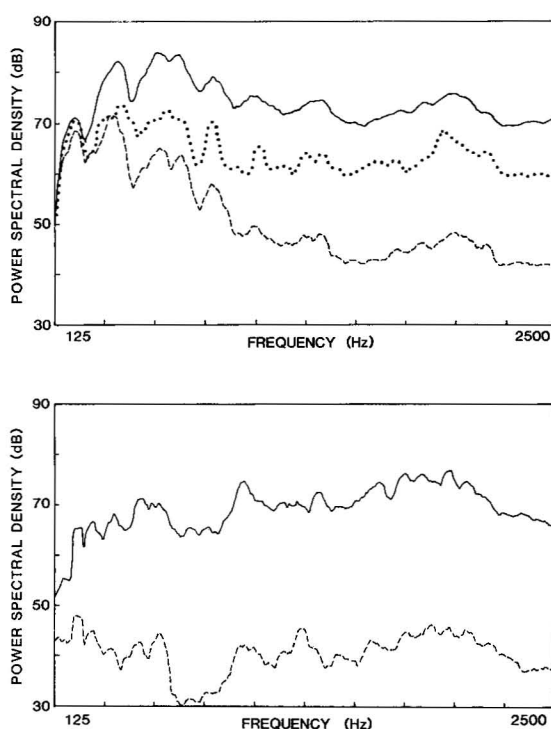


Figure 2. Power spectral density of noise (upper figure) for chain-saw noise outside (—) and inside (···) the earmuffs of the helmet with a fur liner and inside (---) the earmuffs of the helmet without the liner and for (lower figure) grinding noise outside (—) and inside (---) the earmuffs of the helmet.

earmuffs were used without helmet liners. The helmet liners decreased the attenuation by 2 to 6 dB depending on the thickness of the liner. In contrast to shipyard noise, the chain-saw noise was mainly comprised of frequencies below 1 kHz, which contributed considerably to the power spectral density of the noise inside the earmuffs (figure 2). A comparison of the time-

domain blocks of samples from outside and inside the earmuffs for each tool showed that the high frequencies were more attenuated than the low frequencies (figure 3).

The application forces of 49 sets of earmuffs used by forest workers averaged 10.3 N with a range of

6.5–14.5 N. The correlation between application force and the attenuation of the earmuffs was not statistically significant.

Vibration

The weighted acceleration of the chain saws was in the range of 1.8–2.2 m/s². It has been at about this level since 1972 when the first antivibrating chain saws came into professional use, but the impulsiveness of the vibration and the weight of the saws have decreased (24, 47, 48). Because of these developments the daily exposure time has increased and is currently about 5 h a day.

In the shipyard, the weighted acceleration for different grinding machines varied between 0.4 and 6 m/s². Pneumatic hammers clearly generated higher weighted acceleration, varying between 6 and 300 m/s². The weighted acceleration measured on the handle of the tools correlated with the unweighted acceleration measured on the wrist (figure 4). In the shipyard, hand-held power tools are used intermittently, their daily usage averaging 2 h.

Hearing threshold levels

In both groups of workers great variation was found between the predicted and measured individual hearing levels (figure 5). Among the forest workers the measured hearing loss at 4 kHz was not significantly [two-tailed paired t-test $t(184) = 1.083$] different from that predicted by Robinson's model (table 1). The measured hearing loss of the shipyard workers was significantly greater ($t(170) = 8.117$, $P < 0.005$) than that calculated by Robinson's model.

Discussion

In this study the evaluation of noise exposure was affected primarily by the usage time and secondarily by the measured performance of the hearing protectors. Both factors displayed such a large variation that other factors had only a minor effect on the noise exposure evaluation. The use of earmuffs has been mandatory for forest workers since 1971–1973; earlier some workers used their own earmuffs. At present, the earmuff usage time is estimated to be 79 % for forest workers and 93 % for shipyard workers. The attenuation of earmuffs under work conditions is not well known (2, 6, 10, 15). In this study it was measured with a miniature microphone method with an estimated error of only ± 2 dB in frequency response, due to the positioning of the microphone close to the ear canal entrance (4, 6, 7). Our aim was to evaluate the noise level at the external ear in accordance with Robinson's immission level. The sound pressure at the eardrum could be calculated from the noise reduction by the open ear transfer function (6).

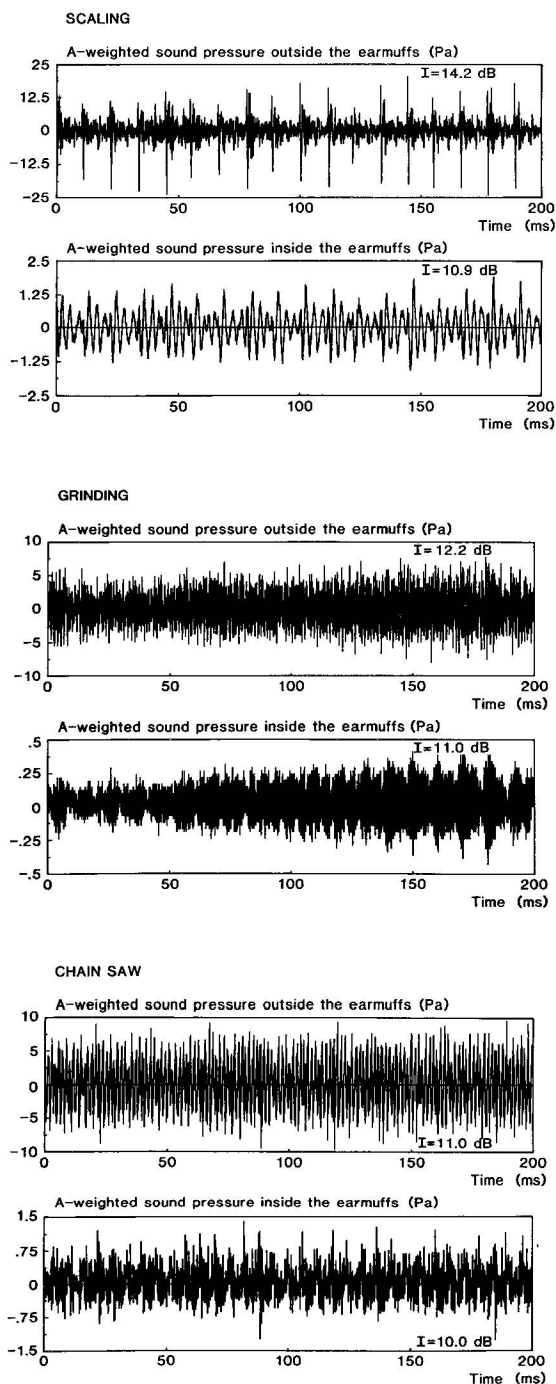


Figure 3. Time-domain blocks measured outside and inside the earmuff for the tools generating the highest impulsiveness (scaling) and lowest impulsiveness (grinding) in the shipyard in comparison to impulsiveness of the chain saw.

The average application force of 12 earmuffs recently tested by a standardized test procedure at the Institute of Occupational Health was 11.7 N with a range of 9.3–14.3 N (13, 14, 22). The application force of the earmuffs used by the forest workers was only slightly decreased and did not correlate with the attenuation. Thus it could not explain the differences in the hearing levels between the two groups of workers.

The earmuff attenuation of the equivalent noise level was greater in the shipyard than in forest work. This result was due to the higher frequency content of the noise in the shipyard than in forest work, and also to the frequency-dependent attenuation of the earmuffs (36). The earmuff attenuation of noise in forest work was less in winter because of the helmet liners, which caused leakage and decreased the attenuation of the earmuffs by 2 to 6 dB (42).

Our earlier studies have shown that forest workers with symptoms of vibration-induced white finger (VWF) have hearing threshold levels that are 10 dB lower than age- and exposure-matched workers without VWF symptoms (41, 42). Due to the wet and cold environment in the forest, the work facilitates the occurrence of VWF symptoms, whereas among shipyard workers in assembly halls a similar activation of symptoms of VWF cannot be expected (39). Forest workers are exposed to equal periods of noise and vibration, since the chain saw runs only when held in the hands. At the shipyard, the length of the exposure to vibration is half of that in forest work but the vibration acceleration is about two times higher. The total energy of weighted vibration acceleration is similar in both groups. We did not observe any excess risk of hearing loss in the groups exposed to vibration.

Vibration measurements at the wrist showed that the hand-arm system operates as a low pass filter resembling the weighting presented in the international standard (38). Therefore, we cannot expect that hand-arm vibration would mechanically interfere with cochlear function.

Robinson's model predicts an age-corrected hearing threshold level that is related to the A-weighted equivalent noise level and to the duration of exposure (44). Robinson's model is exactly defined by individual exposure data, but it neglects individual susceptibility and environmental factors other than exposure time and the total level of exposure to noise (11, 18, 25). These pitfalls might be avoided if a suitable unexposed reference group is selected. Recently, Robinson proposed that it is not generally realistic to compare measured hearing loss with an "otologically normal" base line from an age-matched group, since differences between a normal and a noise-exposed population will include adventitious hearing loss along with the noise-related components (45). Since the mean ages of our groups differed, the selection of the model affected the age correction and, further, the hearing threshold level. The difference due to age correction was less than 2 dB between the groups (with 35- and 43-year mean

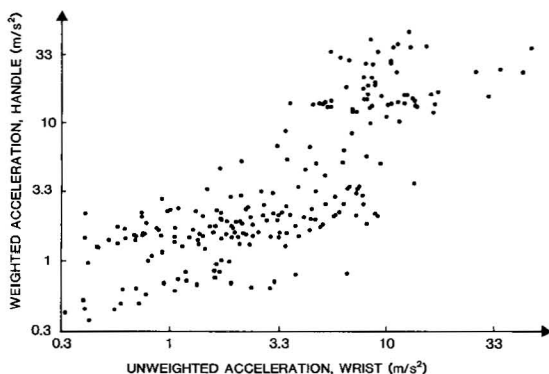


Figure 4. Weighted acceleration in the handles of tools used in the shipyard in comparison to the unweighted acceleration in the corresponding wrists.

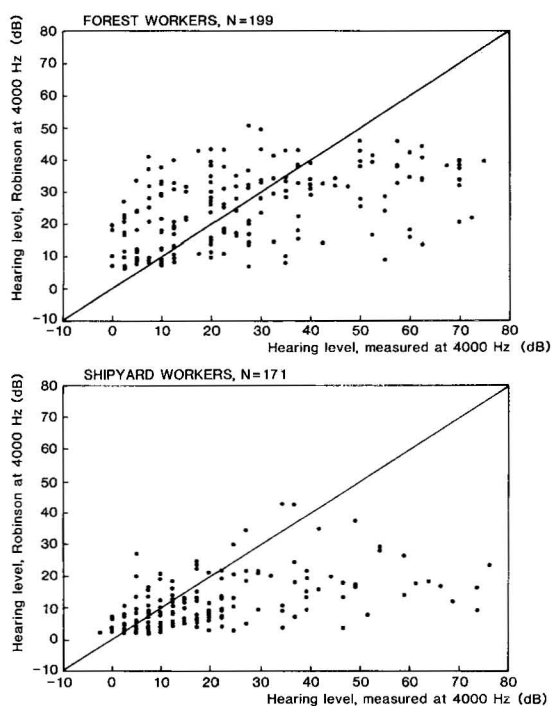


Figure 5. Comparison of hearing levels calculated and measured at 4 kHz in 1986 for forest workers (upper figure) and shipyard workers (lower figure).

ages) when the use of Robinson's model (44) and the proposal for an international standard (23) were compared. This finding does not explain the 10-dB difference between the measured and estimated hearing loss in the group of shipyard workers.

Robinson's model underestimated the risk of hearing loss in the shipyard assembly hall. The noise inside the earmuffs was more impulsive than in forest work. The impulsiveness counteracts the lower noise level inside the earmuffs in shipyard assembly halls and increases the risk of sensory neural hearing loss. Thus the impulsiveness of noise seems to be a prominent fac-

tor explaining the discrepancy found for shipyard workers in Robinson's model. The crest factor method overcomes the difficulties in the analysis of single exponential impulses and is recommended for large epidemiologic studies on workers exposed to noise with different impulse levels but similar total exposure levels.

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