

Hand-arm vibration in the aetiology of hearing loss in lumberjacks

I PYYKKÖ,¹ J STARCK,² M FÄRKKILÄ,¹ M HOIKKALA,² O KORHONEN,² AND M NURMINEN²

From the Institute of Physiology,¹ University of Helsinki, and the Institute of Occupational Health,² Helsinki, Finland

ABSTRACT A longitudinal study of hearing loss was conducted among a group of lumberjacks in the years 1972 and 1974-8. The number of subjects increased from 72 in 1972 to 203 in 1978. They were classified according to (1) a history of vibration-induced white finger (VWF), (2) age, (3) duration of exposure, and (4) duration of ear muff usage. The hearing level at 4000 Hz was used to indicate the noise-induced permanent threshold shift (NIPTS). The lumberjacks were exposed, at their present pace of work, to noise, L_{eq} values 96-103 dB(A), and to the vibration of a chain saw (linear acceleration 30-70 ms^{-2}). The chain saws of the early 1960s were more hazardous, with the average noise level of 111 dB(A) and a variation acceleration of 60-180 ms^{-2} . When classified on the basis of age, the lumberjacks with VWF had about a 10 dB greater NIPTS than subjects without VWF. NIPTS increased with the duration of exposure to chain saw noise, but with equal noise exposure the NIPTS was about 10 dB greater in lumberjacks with VWF than without VWF. With the same duration of ear protection the lumberjacks with VWF consistently had about a 10 dB greater NIPTS than those without VWF. The differences in NIPTS were statistically significant. The possible reason for more advanced NIPTS in subjects with VWF is that vibration might operate in both of these disorders through a common mechanism—that is, producing a vasoconstriction in both cochlear and digital blood vessels as a result of sympathetic nervous system activity.

Subjects exposed to occupational vibration are also often exposed to excessive noise levels. In laboratory experiments noise has been shown to assist the vasoconstriction produced by vibration,¹ probably by activating the sympathetic nervous system. Simultaneous exposure to vibration also seems to act synergistically with noise to cause a noise-induced permanent threshold shift (NIPTS).^{2,3}

The frequency range,⁴ intensity,⁵ duration,⁶ and impulse characteristics of the noise⁷ are physical properties related to the vulnerability to noise. It has been suggested that the variability in the effect of noise on different subjects depends on differing hair cell metabolism or differing blood flow characteristics⁸ or middle ear mechanisms and anatomical factors⁹ or both.

An overactive sympathetic vasoconstrictor reflex

has been considered as the aetiology of vibration-induced white fingers (VWF).¹⁰ The vulnerability to vibration is related to factors such as the frequency range of vibration,¹¹ intensity of vibration,¹² and duration of vibration.¹³ Moreover, the diameter of the lumen of the blood vessels of the hand, smoking habits, and working position have been suggested to explain partly why some subjects are more susceptible to vibration than others.^{14,15}

A common mechanism might operate in both NIPTS and VWF, inducing vasoconstrictions in both the cochlear and peripheral blood vessels. To study this hypothesis we measured the hearing levels of a group of lumberjacks annually for six years. We also recorded symptoms and signs of VWF.

Subjects and methods

SAWS

The noise and vibration of an old model chain saw (1958 Homelite ZIP) in its original condition and

Requests for reprints to: Dr Ilmari Pyykkö, Department of Otolaryngology, University Hospital of Lund, 22185 Lund, Sweden.

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only slightly used was measured, as was the vibration of three saws from the three most common types of chain saws currently used in Finland (Partner P48, Husqvarna 164, and Raket 451). The nine chain saws had been in use for more than 300 hours. The guide bar, chain, and sprocket were replaced with new ones.

NOISE

The noise was measured with equipment suitable for fulfilling the demands of IEC Standard 179¹⁶ and with precision sound level meters (Brüel and Kjaer 2209) with octave filters, IEC 225.¹⁷ A condenser microphone (Brüel and Kjaer 4145) was located near the ear of the operator during continuous work.

The noise dose was evaluated from two lumberjacks with a personal noise dosimeter (Wärtsilä 6074), which they carried during their normal work day. The readings were evaluated after each individual working shift. The measurements consisted of readings made on five work days. The noise dose was expressed in L_{eq} -values (continuous energy equivalent sound level).

VIBRATION

The vibration was measured while cutting from a spruce log slices of uniform shape.¹⁸ An accelerometer was mounted with a screw to the front handle in the direction of the metacarpal bones. The signal was amplified with a charge amplifier (Brüel and Kjaer 2035) and recorded with an FM-type recorder (Brüel and Kjaer 7003). The analyses

were made with a 1/3-octave band real time analyser (Brüel and Kjaer 3347) and the average and its standard deviation were calculated with a mini-computer (Tektronix 4051).

SUBJECTS

The investigations were made in connection with a compulsory health examination of all lumberjacks working for the National Board of Forestry during the years 1972 and 1974-8. Only lumberjacks who had used a chain saw for at least three consecutive years with a minimum of 500 hours a year were included in the study. Table 1 gives the age distribution of the lumberjacks studied in the various years.

VWF-EVALUATION

The lumberjacks completed a questionnaire on their state of health, medication, and symptoms of vibration syndrome. A medical history was recorded, and a physical examination, always by the same doctor, was carried out, concentrating especially on the symptoms and signs indicating VWF. A cold provocation test¹³ was performed on all lumberjacks with a history of white fingers.

VWF was diagnosed when there was a typical history of blanching of the fingers, regardless of the time that had elapsed since the last attack.¹⁹ Other causes, including Raynaud's phenomenon, were ruled out with the history, clinical examination, and results of routine laboratory tests.¹³ Table 2 shows the number of lumberjacks with VWF in the different study years.

Table 1 Age distribution of lumberjacks studied in different years. (Percentages in parentheses)

| Age (yr) | Year of examination | | | | | |
|----------|---------------------|-----------|-----------|-----------|-----------|-----------|
| | 1972 | 1974 | 1975 | 1976 | 1977 | 1978 |
| 20-9 | 3 (4) | 10 (10) | 26 (16) | 31 (18) | 37 (20) | 45 (22) |
| 30-9 | 26 (36) | 37 (37) | 54 (32) | 61 (34) | 59 (31) | 64 (32) |
| 40-9 | 36 (50) | 38 (38) | 66 (40) | 70 (38) | 72 (38) | 73 (36) |
| 50-9 | 7 (10) | 15 (15) | 19 (12) | 19 (10) | 21 (11) | 21 (10) |
| Total | 72 (100) | 100 (100) | 165 (100) | 181 (100) | 189 (100) | 203 (100) |

Table 2 Number of lumberjacks with a history of VWF in the different study years (as a percentage of all lumberjacks of the same age group)

| Age (yr) | Year of examination | | | | | |
|----------|---------------------|---------|---------|---------|---------|---------|
| | 1972 | 1974 | 1975 | 1976 | 1977 | 1978 |
| 20-9 | — | 1 (10) | 1 (4) | 1 (3) | 1 (3) | 1 (2) |
| 30-9 | 9 (35) | 10 (27) | 15 (28) | 16 (26) | 15 (25) | 16 (25) |
| 40-9 | 17 (47) | 17 (45) | 25 (38) | 26 (37) | 28 (39) | 28 (38) |
| 50-9 | 3 (43) | 5 (33) | 8 (42) | 8 (42) | 9 (43) | 9 (43) |
| Total | 29 (40) | 33 (33) | 49 (30) | 51 (28) | 53 (28) | 54 (27) |

HEARING MEASUREMENTS

Hearing was tested in an acoustically treated but non-isolated room where the A-weighted sound level ranged from 22 to 24 dB. The background noise in the testing room showed that at low frequencies (500 Hz and below) the noise was too high to allow the measurement of the 0 dB hearing level,⁹ but at frequencies of 1000 Hz and above it was not. The hearing level according to Burns⁹ is "a measured threshold of hearing, expressed in decibels relative to a specified standard of normal hearing." In the results the hearing level at 4000 Hz was used as an indicator of NIPTS.^{9 20} The occupational noise free period before testing ranged from 15 to 48 h.

A screening audiometer (Maico Ma-19) was used for the hearing measurements; calibration was made annually.²¹ The instructions given to lumberjacks were basically those outlined by Hinchcliffe and Littler.²² The lowest level at which two of the three signals presented were identified correctly was considered as the hearing level. The test proceeded from 1000 Hz to lower frequencies, then back to 1000 Hz and towards higher frequencies. If a discrepancy in the hearing level at 1000 Hz between the two measurements was observed the test was repeated. At the frequency of 4000 Hz, the mean of the hearing level of the right and left ear was used for each lumberjack. During the physical examination the ears were inspected. Lumberjacks with an ear disease or possible effects of noisy jobs other than sawing and noisy hobbies etc were excluded from the subject group.

STATISTICS

The significance of differences between the groups was tested in each case separately with Student's *t*-test for independent samples. Welch's approximate *t*-test was applied if the sample variances differed considerably—that is, if their ratio exceeded two or fell below one-half.²³ Bilateral testing was used. The evidence obtained was gathered by Fisher's method for combining the probabilities of several mutually independent tests.²⁴ As this procedure does not take into account the signs of the separate test statistics, it was not applied if all the differences were not in the same direction. It should be noted, however, that the requirement of independence was not completely satisfied in the case of the results concerning several years as the samples consisted partly of the same subjects. Hence the significance of the statements should be regarded mainly as descriptive.

Results

CHAIN SAW NOISE

Figure 1 presents the noise spectrum of the 1958

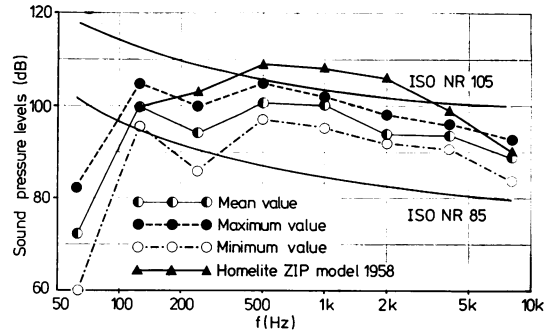


Fig 1 Noise levels of different chain saws including recommended noise levels (ISO, 1970).

Homelite ZIP chain saw. For comparison the lowest, highest, and mean noise levels from seven chain saws currently in use²⁵ and ISO curves NR 105 and 85 are included. The Homelite ZIP exceeded NR 105 and paralleled the NR 108 value. The noises of the currently used chain saws were below NR 105, although at some frequencies they came close to it.

PERSONAL NOISE DOSE

Personal noise dose measurements over one working period showed L_{eq} -values of 96 to 103 dB(A) depending on the condition of the chain saw and the working environment.

CHAIN SAW VIBRATION

Figure 2 shows the 1/3-octave vibration spectrums of nine presently used chain saws, the 1958 Homelite ZIP, and the recommended maximal vibration.²⁶ The chain saw having the lowest vibration paralleled the ISO proposal for the 4-8 h risk limit, but the average values exceeded the ISO proposal. The chain

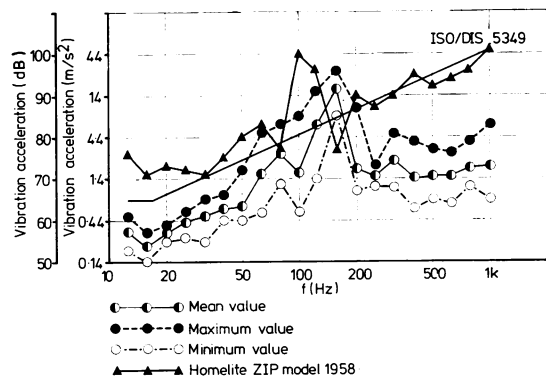


Fig 2 Vibration of nine chain saws (of three different makes) analysed in 1/3-octave bands. Vibration is measured in front handles. Risk limit curves for continuous work are shown (ISO, 1978).

saw with the highest vibration exceeded the permissible value by 10 dB. The result implies that the operation period for the saw with the highest acceleration should be limited to half an hour a day. The Homelite ZIP exceeded the corresponding limit by 20 dB in the 1/3-octave band of 100 Hz. Generally, the highest vibration was measured in the frequency range of 63-250 Hz.

HEARING LEVELS

Figure 3 (a-d) shows the hearing levels at 4000 Hz of lumberjacks in the years 1972-8 when classified in 1978 into different age groups. In the age groups 30-39 ($p < 0.05$) and 40-49 ($p < 0.01$) the lumberjacks with VWF consistently had about a 10 dB lower hearing level than the lumberjacks without VWF.

Table 3 shows the chain saw operating hours, the time with ear muffs, and the hearing level at 4000 Hz in 1978. A statistically significant difference ($p < 0.05$) in the total chain saw operation time was observed in the age group 30-39 years.

Figure 4 (a-d) shows the hearing levels at 4000 Hz in the years 1972-8 according to total chain saw operating time. No lumberjack with VWF in 1978 had operated a saw for less than 5000 h (mean latent period for VWF among these lumberjacks in 1972 was $5600 \text{ h} \pm \text{SD } 2500 \text{ h}$).¹³ In the other groups the lumberjacks with VWF had about a 10 dB lower hearing level than the lumberjacks without VWF. The difference was statistically highly significant in the exposure groups of 5000-9900 h and 10 000-14 900 h ($p < 0.001$ in both groups).

Figure 5 (a-d) shows the hearing levels at 4000 Hz in the years 1972-8 according to the total operation time without ear muffs before 1978. In all groups the lumberjacks with VWF had about a 10 dB lower hearing level than lumberjacks without VWF. The difference was statistically significant in the group who had worked for 10-14 years ($p < 0.01$).

Discussion

Since the 1960s the noise associated with chain

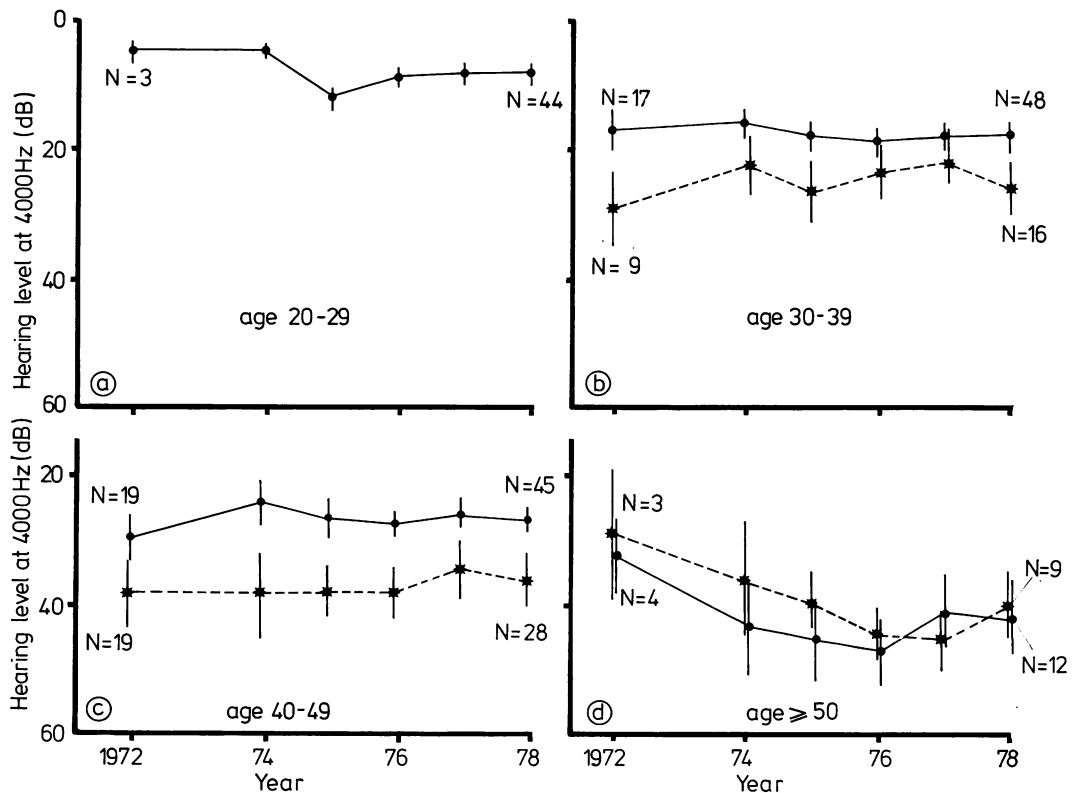


Fig 3(a-d) Hearing level at 4000 Hz in lumberjacks without (●) and with (★) VWF during different years when classified in 1978 according to age. Means and standard errors of mean are given.

Table 3 Hearing levels at 4000 Hz of lumberjacks shown in fig 3, when classified according to the presence of VWF, age group, and duration of use of chain saw and ear muffs in 1978. Mean values are given (standard deviation in parentheses)

| Age (yr) | | Without VWF | | | With VWF | | |
|----------|-------------------|-------------|------------------------------|---------------|----------|------------------------------|---------------|
| | | No | Exposure (hundreds of hours) | Hearing level | No | Exposure (hundreds of hours) | Hearing level |
| 20-9 | Without ear muffs | | 15 (20) | | 49 | | |
| | With ear muffs | | 44 (19) | | 58 | | |
| | Total | 44 | 59 (31) | 9 (9) | 1 | 107 | 5 |
| 30-9 | Without ear muffs | | 48 (31) | | 55 (21) | | |
| | With ear muffs | | 58 (22) | | 71 (22) | | |
| | Total | 48 | 105 (38)* | 19 (16) | 16 | 127 (35) | 26 (17) |
| 40-9 | Without ear muffs | | 69 (38) | | 70 (29) | | |
| | With ear muffs | | 58 (22) | | 65 (25) | | |
| | Total | 45 | 128 (48) | 27 (15) | 28 | 138 (37) | 37 (24) |
| ≥ 50 | Without ear muffs | | 68 (52) | | 63 (17) | | |
| | With ear muffs | | 63 (28) | | 71 (37) | | |
| | Total | 12 | 132 (49) | 42 (20) | 9 | 135 (41) | 39 (16) |

*p < 0.05.

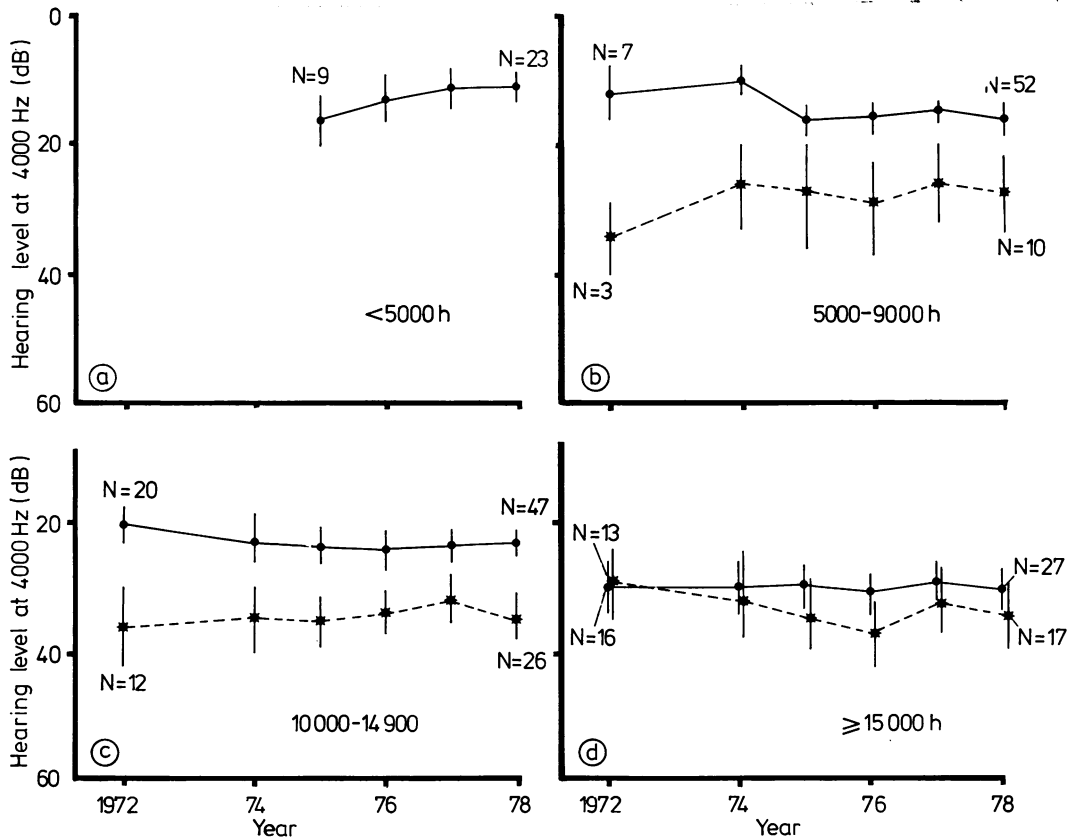


Fig 4(a-d) Hearing level at 4000 Hz in lumberjacks without (●) and with (★) VWF during different years when classified in 1978 according to operation time of chain saw. Means and standard errors of mean are given.

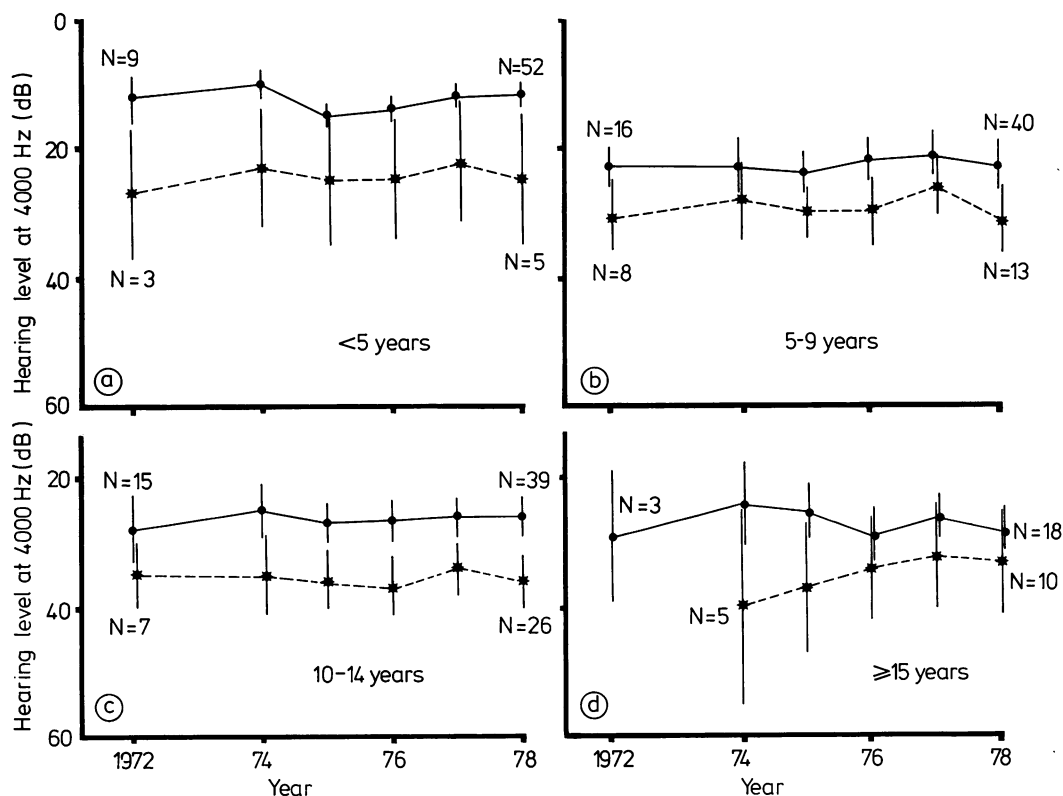


Fig 5(a-d) Hearing level at 4000 Hz in lumberjacks without (●) and with (★) VWF during different years when classified in 1978 according to time exposed to chain saw noise without using ear muffs. Means and standard errors of mean are given.

saws has decreased (table 4) as has the vibration of chain saws in recent years. The vibration measurements made by the Finnish Research Institute of Engineering and Forestry in the 1960s showed that the vibration displacement was 0.1-0.3 m/s² in saws without any vibration isolation.²⁷ This displacement is equivalent to an acceleration of 60-180 m/s² when the frequency is supposed to be 125 Hz, and is in

agreement with the Homelite chain saw vibration measurements made for this study.

The weight of a chain saw nowadays is only about half of what it was in the 1960s, which in turn allows less vibration to spread into the hands and arms.²⁸ All improvements such as this are beneficial in retarding the development of VWF.¹⁵

Safety regulations for noise and vibration were established in Finland as late as 1972. According to these regulations, chain saws with a noise level exceeding the ISO noise rating curve of 105 dB may not be offered for sale. Moreover, the limit for the vibration force in both handles was set at 50 N. This regulation, however, concerns only new, unused saws.

The wear and tear associated with increasing use of a chain saw causes imbalance in the moving parts (cutting chain, engine, isolation of the handles). These characteristically produce an increase in the noise and vibration of the tool. In an earlier study we observed noise levels of up to 116 dB(A) in used

Table 4 Noise levels of chain saws in early 1960s and in 1976

| Type of chain saw | A-weighted sound level dB(A) | | | |
|--|------------------------------|------|---------|--------|
| | Manufactured | Mean | Highest | Lowest |
| Homelite ZIP | 1958 | 113 | — | — |
| 10 professionally used chain saws (Vakola) | 1962 | 111 | 116 | 102 |
| 7 professionally used chain saws (Vakola) | 1976 | 103 | 106 | 99 |

saws.²⁹ Therefore, the noise and vibration exposure during the follow-up period has probably been closer to the measured values of the chain saws from the early 1960s rather than those values measured from chain saws used currently.

Protective measures to prevent noise-induced hearing loss by using ear muffs were taken in Finland in 1972, after which everyone in forest work had to use ear muffs when exposed to noise levels above 85 dB(A). The use of ear muffs varied at first, and even in 1972 some 15% of the lumberjacks did not wear them, for a variety of reasons. The respective figure in 1978 was under 5%. On the other hand, it seems possible that the ear muffs used today do not protect one completely from hearing damage.²⁹ For instance, sympathetic activation and the resulting triggered reflexes start at much lower noise levels than are needed to cause hearing damage.

It might be questioned whether measurements of the hearing level at 4000 Hz are sufficient to describe the hearing damage caused by the noise of a chain saw. The power spectrum of chain saw noise reaches its maximum between 100 and 500 Hz (see fig 1) and causes the greatest deterioration in the cochlea within the frequency range of 1000 to 2000 Hz.⁴ Only a slight decrease, however, occurs in chain saw noise at higher frequencies, and taking into consideration the greater sensitivity of the ear around the frequency of 1000 Hz, the greatest hearing loss can be expected at 4000 Hz.⁴

Learning effects can influence the shape of the hearing threshold curves during the course of time. Because the relation between subjects with VWF and without VWF were rather stable during different years a learning effect does not explain the difference in mean hearing results. Recovery times were, for practical reasons, 15-48 h, not the normally accepted 40-h minimum. This factor seems to be insignificant because the subjects were intermixed according to VWF—for instance, the controls were studied simultaneously with subjects with VWF. The base level of hearing was about the same in groups to be compared despite large differences between individuals.

The reason for lumberjacks with VWF showing greater hearing loss than the lumberjacks without VWF is not known. One possible explanation could be that the hearing loss was at least partly caused by the vasoconstriction of the cochlear vessels triggered by vibration. Local vibration is known to stimulate the sympathetic nervous system³⁰ and when prolonged it may lead to vasoconstriction in the peripheral vessels.³¹ Electrical stimulation of the sympathetic cervical ganglia in animals leads to a decrease in cochlear microphonic potential, explained as the result of decreased blood

flow in the stria vascularis.³² The decrease in blood flow, reaching up to 25%, has been recently confirmed by measuring the penetration of radioactive gelatinous particles of different size in the cochlear vessels.³³

The mechanism by which the subjects with VWF developed greater hearing losses could thus be analogous to the postulated mechanism leading to peripheral vasoconstriction in the vibration syndrome,¹ a sympathetic overactivation that results in vasoconstrictions in the blood vessels of the inner ear. This, when repetitive, can cause muscular hypertrophy in the wall of the vessel by the exercising effect and lead to a decrease in the diameter of the lumen.³⁴ During the rest the flow is only moderately decreased, but during a strong sympathetic stimulation and high metabolic demand, such as during noise and vibration exposure, ischaemia in the target organ supplied by the vessels may result.³⁵

The vibration probably did not interfere mechanically with the cochlear function and cause the difference in NIPTS between the VWF and non-VWF groups, even if the vibration seemed to assist the development of the NIPTS.²³ Low-frequency vibration is transmitted by the bones of the upper extremities into the skull, where its intensity can be high enough (at 100 Hz, 60 dB attenuation³⁶) to cause vibration of the hair cells in the labyrinth.³⁷ The lumberjacks with VWF used somewhat higher compression forces,¹⁵ which allowed a higher amount of vibration to be transmitted along the bones.²⁸ This difference was slight, only 1-2 dB. The practical importance of this difference is small when compared with the fluctuation in the vibration and noise of the saws, and probably does not explain the difference in NIPTS between subjects with and without VWF.

On the basis of aging alone we would expect a 3-6 dB deterioration in the hearing level at 4000 Hz during the follow-up period.³⁸ No deterioration, however, in the hearing levels at 4000 Hz was observed. There are two possible reasons for this. Firstly, during the study the number of lumberjacks increased because of recruitment. The new men were younger and had operated a chain saw less and also had protected their ears at an earlier stage than those lumberjacks already participating in the study in 1972. Furthermore, the level of noise and vibration to which the newer men were exposed was lower, as could be shown by comparing measurements made in chain saws of the early 1960s and in those used now. These factors would all produce an improvement in the mean value of the hearing threshold level. When the same lumberjacks were followed from 1972 to 1978 a deterioration in the hearing level was observed.²⁹ Secondly, especially in the older and more

exposed lumberjacks, when the NIPTS reaches a certain degree the deterioration of the hearing level at 4000 Hz ceases, while the deterioration continues at adjacent frequencies (at 2000 and 8000 Hz).⁹ Although Delany³⁹ and Robinson⁶ have shown the importance of practice in audiometric measuring, we have discounted this factor as an explanation for our results.

Conclusion

The results indicated that the NIPTS in the lumberjacks increased with advancing age. It was also dependent on the duration of exposure and the use of hearing protectors. There was a significant difference between lumberjacks with and without VWF; the former showed greater hearing loss. Vasospastic phenomena in the fingers seems, therefore, to be linked to the threshold shift in hearing.

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The May 1981 issue

THE MAY 1981 ISSUE CONTAINS THE FOLLOWING PAPERS

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B M HAUSEN AND H SCHMALLE

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J P LYONS AND H CAMPBELL

Mortality of workers certified by pneumoconiosis medical panels as having asbestosis
G BERRY

Prevalence of byssinosis in Swedish cotton mills
P HAGLIND, MONICA LUNDHOLM, AND R RYLANDER

An investigation of operating theatre staff exposed to humidifier fever antigens
A COCKCROFT, J EDWARDS, C BEVAN, I CAMPBELL, G COLLINS, K HOUSTON, D JENKINS, S LATHAM, M SAUNDERS, AND D TROTMAN

Ventilatory function changes over a workshift
H D DIMICH AND T D STERLING

Hanford radiation study III: a cohort study of the cancer risks from radiation to workers at Hanford (1944-77 deaths) by the method of regression models in life-tables
G W KNEALE, T F MANCUSO, AND ALICE M STEWART

Lymphocyte reactivity of workers exposed to carcinogenic and non-carcinogenic chemicals
S KUMAR, G TAYLOR, WENDY HURST, P WILSON, AND C B COSTELLO

Urinary β_2 microglobulin in the biological monitoring of cadmium workers
MORAG STEWART AND E G HUGHES

Arginase and kallikrein activities as biochemical indices of occupational exposure to lead
JADWIGA CHMIELNICKA, ELZBIETA KOMSTA-SZUMSKA, AND JADWIGA A SZYMANSKA

Arsenic and selenium in lung, liver, and kidney tissue from dead smelter workers
P O WESTER, D BRUNE AND G NORDBERG

Renal cadmium overload without nephrotoxicity
R R GHOSE, W D MORGAN, AND P E CUMMINS

Enhanced excretion of thioethers in urine of operators of chemical waste incinerators
R VAN DOORN, CH-M LEIJDEKKERS, R P BOS, R M E BROUNS, AND P TH HENDERSON

Search for benzidine and its metabolites in urine of workers weighing benzidine-derived dyes
P F MEAL, J COCKER, H K WILSON, AND J M GILMOUR

Experimental exposure to toluene: further consideration of cresol formation in man
W WOIWODE AND K DRYSCH

For discussion
Assessment of risk by biological monitoring
D GOMPERTZ

Notes and miscellanea
Hanford radiation study
S C DARBY AND J A REISSLAND

Book reviews

Information section