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High impulse acceleration levels in hand-held vibratory tools

An additional factor in the hazards associated with the hand-arm vibration syndrome

by Jukka Starck, MSc¹

STARCK J. High impulse acceleration levels in hand-held vibratory tools: An additional factor in the hazards associated with the hand-arm vibration syndrome. *Scand J Work Environ Health* 10 (1984) 171—178. The measurement of the root-mean-square (rms) acceleration of vibration does not take into consideration the short high peak values of the vibratory signal, which may be a hazard contributing to the development of vibration-induced disease. A method for evaluating the impulse character of vibratory signals is given, and impulsiveness is defined as the difference between the peak and rms signals. Measurements were taken during pedestal grinding, during chain sawing with three different generations of saws, and during chiseling with a pneumatic hammer. The measurements comprised (i) analyses done according to the International Organization for Standardization (ISO) draft, (ii) an evaluation of impulsiveness, and (iii) an analysis of the short-time history transient. The risk of vibration-induced white fingers was estimated by the ISO method, and the results were compared with those observed. It was found that the analysis of impulsiveness provided additional data and partly explained the observed symptoms of vibration-induced white fingers. The parameters for the impulsiveness of the vibration signal agreed with the short-time history analysis.

Key terms: chain saws, impulse vibration, pedestal grinding, pneumatic hammer, risk assessment.

The hazardous effects of occupational exposure to vibration are influenced by several factors related to work conditions, eg, the physical characteristics of vibration, how the tool is handled, biological susceptibility, and differences in the work involved (20). The risk assessment of hand-transmitted vibration should take all these factors into account, even though their individual importance in the etiology of vibration syndrome is not clearly known.

So far the magnitude of vibration has been expressed as either root-mean-square (rms) acceleration (m/s^2) or acceleration level (dB) (4). The measurements do not take the short and high peak values of the vibration signal into consideration. The content of the high peaks in the signal, ie, the impulse character of vibration in some occupations, is important because high-frequency components may be more hazardous in the etiology of vibration syndrome than has been thought (1, 21).

The purpose of the present report is to measure and analyze the high peak level of impact vibration from different tools and to relate the results to the observed prevalence and latency data from exposed

workers. The following three types of vibration tools were evaluated: grinding wheels (pedestal grinding), chain saws, and a pneumatic hammer.

Materials and methods

Pedestal grinding

Castings were cleaned manually by an operator who pressed the castings against a grinding wheel. The constant circle speed of the wheel was 47 m/s. Two different types of grinding wheel were measured, one being made of corundum and the other of zirconium corundum. The corundum wheel had not caused vibration-induced white fingers in any of the grinders, whereas the zirconium corundum wheel proved to be very hazardous in that all the workers using such a wheel had contracted the syndrome within one year (18).

The roughness, hardness, and bond of the wheels were the same, but the abrasion material was either corundum or zirconium corundum mixed with silica. The eccentricity of each of the grinding wheels was the same. The weight of the castings cleaned manually varied between 0.5 and 10 kg. The measurements were taken when a casting weighing 5 kg was being cleaned. The same operator was used throughout all the measurements.

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Chain saw

Three different types of chain saw were included in the measurements. They were selected in order to represent three generations of saws. The oldest (Homelite ZIP) was manufactured in 1958 and had no vibration isolation. The second (Partner R22) was manufactured in 1972 and represented the first type of antivibration chain saw. The third saw (Raket R 420) was the most up-to-date; it was manufactured in 1982. All of the saws were in good condition. Their technical specifications are shown in table 1.

Vibration was measured from the handle of the chain saw when slices of pine or spruce logs were being cut. The logs were horizontally supported on a bench during sawing. The operators, professional forest workers, sawed downwards and upwards in turn from four to six times (19).

Pneumatic hammer

Vibration was measured from a pneumatic hammer (Atlas Copco type BHV-22) used by stoneworkers. The diameter of the piston of the hammer was 22 mm, the length of the blow was 30 mm, the frequency of the blow was 83 strikes/s, and the hammer weighed 1.4 kg. During the measurement the operator chiseled gray granite. The air pressure operating the pneumatic hammer was 6 kg/cm² (600 kPa).

Definition of impulsiveness

The primary quantity used to describe the magnitude of the vibration is still rms acceleration, which is normally expressed in terms of meters per second squared. If the impulses are short, the energy level remains low in comparison with the peak level. This phenomenon led to the assessment of impulsiveness on the basis of the difference between the peak and rms signals (6). The shorter the impulse, the greater the difference between the peak and the rms levels. This difference (I) is related to the crest factor of the signal and can be expressed by the formula

$$I = L_{\text{peak}} - L_{\text{rms}} \quad (\text{eq 1})$$

The definition is suitable for the continuous analysis of randomly varying vibration signals. The ana-

lytic functions were the cumulative distribution function $F(I)$ for impulsiveness (equation 1) and the short-time history of the signal. From the cumulative distribution function the impulse indices I_{10} , I_1 , and $I_{0.1}$ were selected to compare the impulsiveness of the different vibration signals. The impulse indices gave impulsiveness I in decibels that corresponded to 10, 1, and 0.1 percentage values (17).

Vibration measurements

Vibration was measured from the casting, from the handle of the chain saw, and from the pneumatic hammer. To mount an accelerometer to the casting, a metal piece was welded, and a mechanical filter [Brüel & Kjaer (B&K) UA 0553] and an accelerometer (B&K 4375) were fastened to the metal piece by a screw. The measurements were taken from the casting only in the horizontal direction because this direction had been found to generate the highest level of vibration (18). To measure vibration from the chain saw, an accelerometer and a mechanical filter were mounted on the front handle of the saw by a hose clamp to which a steel stud had been welded (19). The direction of the accelerometer was vertical so as to approximate the direction of the operator's third metacarpal bone. Accelerometers and mechanical filters were fixed to the chisel head of the pneumatic hammer by the method used for the casting and to the barrel of the hammer by the method used for the handle of the chain saw. The main axis of the accelerometers was in the direction of the blow of the hammer.

The signal was amplified (B&K 2635) and recorded on a tape recorder (B&K 7003) for further laboratory analysis. The frequency range of the sampling was 2 Hz–10 kHz; in this range the frequency response was linear within 1 dB (figure 1, part a).

Laboratory analysis

The recordings were replayed on a real-time analyzer (B&K 2131), and the total acceleration level and weighted acceleration level according to the ISO draft (4) were calculated from the average one-third octave spectrum of 20 to 50 spectra with the use of an averaging time and sampling interval of 0.5 s (figure 1, part b). The length of the sample analyzed for the pedestal grinding and chiseling was 10 s, and that for the chain sawing, from 10 to 25 s. It was not possible to take longer continuous recordings because the work phase, ie, the cleaning, in the case of the castings lasted this period. For the operation of the chain saws, one sample comprised the cutting of several slices of a log. The results for pedestal grinding were calculated from one sample because all the castings were identical. Five samples were collected for

Table 1. Technical specifications of the three chain saws representing different generations.

Specification	Make ^a		
	Homelite ZIP (1958)	Partner R 22 (1972)	Raket R420 (1982)
Weight (kg)	11.6	9.0	5.2
Cylinder volume (cm ³)	82	55	49
Idling speed (s ⁻¹)	25	36	38
Racing speed (s ⁻¹)	102	200	215

^a Year of manufacture in parentheses.

sawing, two for chiseling. The vibration levels (L) were based on the formula

$$L = 20 \log a/a_0 \text{ dB}, \quad (\text{eq } 2)$$

where a = rms acceleration (m/s^2) and a_0 = reference acceleration of 10^{-6} m/s^2 .

The assessment of risk according to the ISO draft (4) should be based on a daily exposure time of 4 h. For different daily work periods the level of exposure to vibration was normalized to 4 h with the formula

$$a_{w4} = (T/4)^{0.5} a_{wT}, \quad (\text{eq } 3)$$

where a_{w4} = the frequency-weighted 4-h energy equivalent acceleration (m/s^2) and a_{wT} = the frequency-weighted equivalent acceleration (m/s^2) for a time of T hours.

The probability distribution function for I (equation 1) was analyzed with a fast Fourier transform function analyzer (Hewlett Packard 5420A) that replayed the signal through the rms peak detector (Wärtsilä L674) (figure 1, part c). The cumulative probability distribution function $F(I)$ of I was calculated by a microcomputer (Luxor ABC 80), which also showed the selected impulse indices I_{10} , I_1 , and $I_{0.1}$. The impulse indices were calculated from the same number of experiments as the total and weighted acceleration values.

A detailed time-history analysis was carried out with a transient recorder (B&K 7502) and a microcomputer (Luxor ABC 80) for signals of 100-ms duration (figure 1, part d). These short-time histories, 100 ms in duration, were displayed by the joining of recurrent 10-ms samples, which were analyzed at the bandwidth of 12.8 kHz.

Results

High impulsiveness occurred for vibration at the low probability levels. The cumulative distribution function was shown only at probabilities from 0 to 15 %, as these probabilities were regarded to be the most suitable for this study (figure 2).

The impulsiveness increases from left to right in figure 2. The highest value was measured from the chisel head, and the lowest from the third-generation chain saw. In pedestal grinding the impulsiveness of the vibration caused by the zirconium corundum wheel proved to be significantly higher than that of the corundum wheel. The impulse character of the vibration of the chain saws decreased from generation to generation. The weighted accelerations were about the same in the second- and third-generation saws.

Figure 1. Block diagram of the equipment used for the recordings and the analyses (a) in the field, (b) in the laboratory according to ISO DIS 5349 (4), (c) in the laboratory for the analyses of impulsiveness, and (d) in the laboratory for the analyses of time history. (B&K = Brüel & Kjaer, HP = Hewlett Packard)

Figure 2. Cumulative distribution function $[F(I)]$ for (a) pedestal grinding, corundum wheel; (b) pedestal grinding, zirconium corundum wheel; (c) a first-generation chain saw; (d) a second-generation chain saw; (e) a third-generation chain saw; (f) a chisel head, and (g) the barrel of a pneumatic hammer.

Figure 3. Weighted acceleration and impulsiveness of three different generations of chain saws. (▲ first generation, ● second generation, ■ third generation)

Table 2 shows the vibration parameters as measured for different tools and calculated according to the ISO draft (4) and according to the amount of impulsiveness (figure 2). The pneumatic hammer and, especially, the chisel head generated the highest vibration with respect to both the equivalent acceleration and impulsiveness. The corundum and zirconium corundum grinding wheels gave off the same weighted acceleration values, but the impulsiveness of the vibration generated by the zirconium corundum wheel was higher than that generated by the corundum wheel. Of the different chain saws the first-generation saw gave off the highest weighted and unweighted acceleration, as well as the greatest degree of impulsiveness. No differences were observed in the weighted acceleration of the second- and third-generation chain saws, whereas the unweighted acceleration value and the impulsiveness of the vibration were higher for the second-generation chain saw than for the third-generation saw.

The weighted acceleration a_{wT} and impulsiveness I_1 analyzed from the measurements of vibration for each chain saw are presented in figure 3. The vibration of the chain saws was separated according to the generation of the saw. The range of the weighted acceleration in the different experiments was 8.0–14.4 m/s^2 for the first generation, 1.8–2.7 m/s^2 for the second generation, and 2.2–2.8 m/s^2 for the third generation. The corresponding ranges for impulsiveness I_1 were 15.3–18.6 dB, 13.6–16.0 dB, and 12.1–12.9 dB. The weighted acceleration was about the same for the second- and third-generation chain saws, but the impulsiveness was the lowest for the third-generation saw.

Transient analyses were done in order to find an explanation for the results shown in figure 2 and table 2. The chisel head generated short peaks that occurred regularly at intervals of 12 ms and corresponded to a blow frequency of 83 Hz (figure 4F).

The peak acceleration in the barrel of the chiseling hammer was reduced to about one-eighth of the acceleration of the chisel head (figures 4F & 4G). In

Table 2. Results of the measurements of the vibration parameters. (a_{wT} = frequency-weighted equivalent acceleration for a time of T hours; T = daily work period, estimated; a_{w4} = frequency-weighted 4-h energy equivalent acceleration; a_{tot} = unweighted total acceleration in the frequency range of 8 Hz–10 kHz; i_{10} , i_1 , $i_{0.1}$ = impulse indices for the percentage values of 10, 1 and 0.1, respectively)

Tool	a_{wT} (m/s^2)	T (h)	a_{w4} (m/s^2)	a_{tot} (m/s^2)	i_{10} (dB)	i_1 (dB)	$i_{0.1}$ (dB)
Pedestal grinding							
Corundum wheel	15	7	20	370	15	18	20
Zirconium corundum wheel	15	7	20	270	17	21	23
Chain saw							
First generation	11	2–3	9	380	16	19	21
Second generation	2	3–5	2	32	11	14	16
Third generation	2	5	2.2	8	8	12	14
Pneumatic hammer							
Chisel head	110	5.5	130	4,700	22	26	29
Barrel	17	5.5	19	680	19	22	25

pedestal grinding the short peaks occurred randomly at intervals of several milliseconds (figure 4B). For the chain saws the transient analysis showed the attenuation of vibration that occurred over the three generations. The first generation chain saw had regularly occurring peaks at 8-ms intervals that corresponded to a combustion frequency of 125 Hz (fig-

ure 4C). In the second-generation chain saw the peaks were strongly reduced (figure 4D), and in the third-generation saw the peaks disappeared (figure 4E).

The risk assessment of vibration-induced white fingers was done according to the ISO method (4). Both the 10 and 50 percentiles were evaluated. Table 3 shows the expected values in comparison with the ob-

Figure 4. Transient recordings of vibration: (A) pedestal grinding, corundum wheel; (B) pedestal grinding, zirconium corundum wheel; (C) first-generation chain saw; (D) second-generation chain saw; (E) third-generation chain saw; (F) chisel head; and (G) barrel of a pneumatic hammer.

Table 3. Expected latency period and prevalence of vibration-induced diseases assessed according to ISO DIS 5349 (4) in comparison with the observed latency and prevalence.

Tool	a_{w4}^a (m/s ²)	Vibration-induced disease				Reference
		Expected latency period (years)		Observed latency period (years)	Observed prevalence (%)	
		Prevalence 10 %	Prevalence 50 %			
Pedestal grinding						
Corundum wheel	20	1.3	3.2	>5	Not known	Starck et al (18)
Zirconium corundum wheel	20	1.3	3.2	<1	100	Starck et al (18)
Chain saw						
First generation	9.0	3.3	7.5	<5	40	Pyykkö et al (13)
Second generation	2.0	15.0	33	<10	16	Pyykkö et al (14)
Third generation	2.2	13.7	30.5	>25	<7	Pyykkö et al (13)
Pneumatic hammer						
Chisel head	131	0.2	0.5	6	75	Färkkilä (personal communication)
Barrel	19	1.6	3.5	9	50	Färkkilä (personal communication)

^a Measured for this study.

served ones (13, 18, & M Färkkilä, personal communication).

Comparisons were made between the expected and observed exposure times for different tools. Agreement was found for chain saw vibration. In the case of pedestal grinding, however, the ISO draft (4) underestimated the hazardous effects of vibration. The prevalence of vibration-induced white fingers among the grinders would presume a weighted acceleration of about 55 m/s², but in this study it was only about 15 m/s².

Discussion

The hazard of vibration-induced white fingers in relation to vibration level

Standardized methods for the analysis of vibration are restricted to measurements of frequency-weighted vibration acceleration and daily exposure times. Safe exposure limits are not defined, but the draft is based on a latency period for vibration-induced white fingers at probability levels of 10 to 50 %. This estimation is given as a function of the weighted acceleration value, which should then be normalized to correspond to a daily work period of 4 h (table 2).

The ISO draft (4) provides a good method for estimating the risk of vibration-induced white fingers in lumbering. In a follow-up study of vibration-induced disease among forest workers, the prevalence of vibration-induced white fingers has decreased from 40 to 7 % between 1972 and 1980 (13). At the same time the weighted acceleration decreased from about 10 to 2 m/s² because of the use of antivibrating chain saws (3, 14, 15, 21, 22). At the beginning of the 1970s the latency period for vibration-induced white fingers was, on the average, five years; it is now longer (13). These findings agree well with the ISO proposal for

the risk assessment of vibrating tools for chain saws used before and after 1972.

The prevalence of 7 % in 1980 may be an overestimation of the hazardousness of vibration generated by the third-generation chain saws, since the prevalence was also still probably influenced by second-generation saws.

However, I found that the ISO draft (4) was not suitable for the risk assessment of human exposure to vibration in different occupations. In a foundry where pedestal grinding is used to clean small castings, new and more effective grinding machines with a different type of grinding wheel caused vibration-induced white fingers in all the workers after a period of one year (18). The weighted acceleration values did not differ significantly between the old and new grinding wheels (17). Moreover, the vibration in pedestal grinding proved to be almost the same as that of the uninsulated chain saws of the 1960s.

The new grinding machines allow the castings to be pressed towards the wheel with more force than the old machines. The transmission of vibration from the casting to the hand is increased (11), as is the static load on the muscles during the grinding operations. These factors should also be considered when the risk of vibration-induced disease is being assessed.

The present results confirmed that conventional methods of measuring vibration do not reveal all its hazardous characteristics. I observed high impact components of vibration in the tools regarded to be the most hazardous. The highest impacts were observed for the pneumatic hammer, particularly the chisel head, followed by pedestal grinding wheels, and chain saws.

The additional data concerning the high values of peak acceleration measured for the tools may partly explain the increased hazard associated with certain tools. For example high impulse indices were ob-

tained for pedestal grinding when the zirconium corundum wheel was used. As reported earlier (18), this wheel also caused a drastic outbreak of vibration-related symptoms among grinders. Thus the impact component of some tools can be a factor crucial to the severity of vibration-induced white fingers.

Physiological aspects of impulsive vibration

In previous reports it was suggested that the impulsiveness of vibration may create shock waves in tissues, and these waves may be transmitted at a higher velocity and to larger body areas than nonimpulsive vibration (11, 18). Thus high peak accelerations may contribute to the hazards associated with vibration by two different mechanisms. High impacts may powerfully distort the tissues and shear the endothelium of capillary beds, an event that leads to leakage and capillary dilation (9). This situation has been reported in connection with laboratory animals exposed to vibration (7, 16), and it may be responsible for the erythema and swelling of the fingers observed after exposure to vibration (22). Furthermore, since the tactile end organs of the fingers, ie, quickly and slowly adapting skin receptors and Pacinian corpuscles, respond to sinusoidal vibration in a phase-locked manner (5, 8), these receptors respond to one impulse with one spike. Since impulsive vibration spreads to larger body areas, more receptors are also recruited. The sensory responses to vibration are enhanced through temporal and spatial summation, and, as a result, impulsive vibration may facilitate somatosensory reflexes and thereby contribute to the injuries caused by vibration (12).

Technical aspects of measuring impulsive vibration

General purpose accelerometers of delta shear construction were used for the measurements to allow the measurement of peak accelerations of up to 250,000 m/s². The accelerometers were mounted on a low-pass mechanical filter, a procedure which is recommended to avoid the nonlinear effects caused by subjection to extreme accelerations, eg, those generated by percussive tools. Otherwise the linearity of the measurements is in doubt due to the direct-current shift in transducers (10).

The cumulative distribution function was selected to describe impulsiveness according to equation 1. Only that part of the function which revealed the distribution of the values for the highest impulsiveness has been shown. In addition the indices for impulsiveness were selected to describe the highest such values. The results in figure 2 and table 2 show that any of the selected indices are appropriate for describing impulsiveness, as the difference between the chosen index for different tools remains almost constant. However, limitations in the dynamic range, and possible disturbances in the signal, can cause

error in $I_{0.1}$. The highest impulses may not be described by I_{10} . These limitations would support the selection of I_1 , if only one index is to be shown (figure 3).

The short-time recordings were 100 ms in duration. At the lowest sufficient bandwidth of 12.8 kHz, the digital signal analyzer (Hewlett Packard 5420A) can handle samples 10 ms in duration. For samples longer than 10 ms a transient recorder (B&K 7502) had to be used. The short-time history was analyzed with recurrent 10-ms samples which were joined together (figure 4). The peaks were then displayed without leakage caused by the limited number of points on display. This method was applied to display several recurrent impulses in order to obtain information about the randomness of the signal with respect to both peak amplitudes and the repetition rate.

The parameters selected for the impulsiveness of the vibration signal agreed well with the short-time transient analysis. The highest impulsiveness was analyzed in the chisel head, and the recorded values corresponded with the results for the short-time history analyses (figure 4).

In previous studies vibration was measured also from the wrist (2, 18). It was found that the transmission of vibration at high levels of acceleration is not necessarily linear. This nonlinear transmission from the vibrating tool to the wrist occurs when impulsive vibration is being generated, the reason being the short duration of the high peak values in the vibration signal. Our method of measuring vibration in the wrist is not suitable for high impulse vibration because of the lower limiting frequency response caused by the mounting of an accelerometer to the wrist.

Conclusion

Insufficient measurements have been carried out to date to allow conclusions or practical proposals to be made on how the impulse character of vibration signals should be taken into account in the assessment of risk. The analysis of high impulse acceleration peaks obtained by the method presented in this report could provide additional data necessary to improve the assessment of the risk involved in exposure to hazardous hand-transmitted vibration.

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