Vibration Injury Network

Research Network on Detection and Prevention of Injuries due to Occupational Vibration Exposures

Evaluation of occupational exposures to hand-transmitted vibration : frequency weighting and exposure duration (a preliminary survey)

Appendix H4A to Final Report

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Abstract

This document is a non exhaustive survey of international literature on two important parameters when assessing hand transmitted vibration exposure :

- The frequency weighting curve. The way it was developed in the sixties and alternative approaches to determine more appropriate frequency weighting curves. Although one of the main target of users of the ISO 5349 standard is to predict the occurrence of vibration white finger, the recommended method for evaluating exposure levels is based on operator perception of vibration. At low frequency the perception is transmitted to the arm therefore the perception is high. The perception greatly decreases with frequency with the reduction of vibration transmissibility throughout the hand arm system. However some researchers noted that the VWF hazards associated with some low frequency tools such as breakers or rammers are low. They suggested that the standardised weighting curve is not adapted for the assessing of the VWF hazards and proposed to not weight the vibration emitted by tools. Alternative methods based on experiments investigating acute physiological responses and epidemiological results should be preferred to develop new weighting curves. However there are difficulties to find objective and repeatable tests to quantify acute adverse effects. Moreover the links between acute adverse effects and health risks are not well established. Analysis of epidemiological data to investigate the best fit of different combinations of physical parameters is never easy because of the many cofactors which may contribute to the observed health effects. With these restrictions in mind, this survey shows clearly the necessity to revise the weighting curve so as to reinforce the weight of mid and high frequency component of hand-transmitted vibration.

- The daily exposure duration. The validity of estimates of duration of exposures to hand transmitted vibration. Most publications are silent on the difficulty to estimate the exposure duration in the field, which casts a strong doubt on the validity of results.

1. Introduction

Present methods of measuring the severity of hand-transmitted vibration exposures currently advocated in national and international standards have been reviewed several times by different authors (e. g. Griffin - 1990, 1994, 1995, 1997 ; Nelson & Griffin – 1992 ; Bovenzi - 1994, 1998).

The ENV 25349 (1992) and project ISO 5349 and many national standards assume that some characteristics of vibration (magnitude, frequency, duration) represent the principal exposure variables which account for the potential harmful effects on the hand arm system. Although the evaluation method (frequency weighting and other aspects of the method) is not based on the development of vibration-induced white finger, all current standardised assessments pretend to predict the occurrence of finger blanching. Standardised dose-effect relationships between the energy-equivalent acceleration and the prevalence of finger blanching were developed by extrapolation and simplification of epidemiological results. In annex A of the ENV 25349 the predicted prevalence of finger blanching is assumed to be directly proportional to the daily duration of vibration exposure, proportional to the square of the acceleration magnitude, proportional to the square of the years of exposure, and inversely proportional to the square of the vibration frequency (at frequencies above 16 Hz).

The objective of this document is to focus on two specific points on which researchers have progressed slowly these latter years :

- The frequency weighting curve, the way it was developed in the sixties and alternative approaches to determine more appropriate frequency weighting curves.
- The validity of estimates of duration of exposures to hand transmitted vibration.

2. Frequency weighting curve

2.1. Standardised frequency weighting

According to the ENV 25349 standard, vibration acceleration should be weighted in each of the three axes by a frequency weighting curve which has slopes of 0 dB below 16 Hz and –6 dB per octave above 16 Hz up to 1250 Hz (see figure 1). This means that the sensitivity of the hand arm system to acceleration is presumed to be independent of frequency below 16 Hz but reduces in inverse proportion to the vibration frequency between 16 and 1250 Hz. The present frequency weighting is derived from results obtained by Miwa in 1967 where he asked 10 subjects to compared the perception of different sinus signals in the frequency range 3 to 300 Hz. He assumed that the highest the perception, the highest the hazards. At low frequency the vibration is transmitted to the full arm and therefore the perception is high. The perception greatly decreases with frequency with the reduction of vibration transmissibility throughout the hand arm system. This was checked again by Stelling and

Dupuis (1996) who found similar subjective equal sensation contours. However they found different sensitivity according to the vibration axis.

Thus the standardised frequency weighting curve roughly reflects the vibration sensation in the human hand extrapolated up to 1000 Hz. Although such sensations may be useful when assessing the

sensory effects of hand-transmitted vibration, they are less obviously suitable for predicting injuries induced by vibration such as vascular disorders.

Griffin (1997) showed that the weighting greatly reduces the importance of intermediate and high frequency vibration emitted by tools. The standardised frequency weighting has an enormous effect on the exposure response relation for VWF. If the vibration frequency is halved, the daily duration of exposure must be decreased by a factor of four, or the years of exposure must be decreased by a factor of two (assuming the acceleration magnitude and the predicted prevalence of VWF remain unchanged) !

Griffin (1997) compares weighted and unweighted accelerations of 20 different tools with various frequency spectra. He shows that because of the shape of the frequency weighting, the rank order of importance of tools is significantly changed. When choosing between tools, two tools with different spectra but the same weighting acceleration will not have the same unweighted magnitude and may not have the same potential for causing injury. Another important result of Griffin study (1997) is that although current standards require measurements of vibration from at least 8 to 1000 Hz, almost identical values of weighted acceleration would have been obtained by restricting consideration to frequencies below 250 Hz. This is because of the important attenuation above 250 Hz due to the slope of the weighting curve.

Pelmear et al (1989) noted that the VWF hazards associated with some low frequency tools such as breakers or rammers are low. They suggested that Miwa weighting curve is not adapted for the assessing of the VWF hazards. The National Institute for Occupational Safety and Health (NIOSH) proposes the use of unweighted acceleration to assess vibration exposure and health risk in the United States (1989).

2.2. Frequency weighting based on biomechanic measurements

Burström & Lundström (1988), Lunström & Burström (1994), Sorensson & Burström (1996) hypothese that equal risk is associated to equal absorbed power. This is by no means a new concept. In the field of whole-body exposure to vibration this subject has been reviewed in a recent paper by Mansfield and Griffin (1998).

The vast majority of all the experimental work aimed at taking "direct" measurements of the power absorbed by the hand and arm, has been performed by the Swedish group at NIWL. Results are usually presented drawing curves of absorbed power in one - third octave bands.

Weighting curves for risk assessment procedures are traditionally used in connection with measured values of acceleration. A similar choice has been made for the weighting curve calculated in this document, in order to enable comparisons with other previous curves. This has required taking the following steps :

1. All data have been normalised with respect to a selected frequency (10 Hz).
2. Following the procedure outlined by Mansfield & Griffin (1998) for a similar study of whole-body frequency weighting, The square root of data of absorbed power were taken. Indeed, because power depends on velocity (or acceleration) squared, the square root of power is a more convenient choice than of power, as it depends linearly on acceleration (the constant of proportionality is the frequency weighting, in appropriate units).
3. Experiments have all been performed at constant rms. velocity. Because $a = 2\pi fv$, data have been divided by $2\pi f$.

The resulting frequency weighting is such that when multiplied by acceleration it provides a value proportional to the square root of absorbed power.

Results have been derived from values of absorbed power calculated by Burström & Lundström (1988) and Lundström & Burström (1994). An additional data set by Sorensson & Burström (1996) has not been included since power has been calculated for random vibration, at very low vibration levels and only for the X axis. Neither of these three features is negative in itself, they just happen to disagree with the method followed by the previous investigators.

From the curves given in Figure 1, the following comments can be made :

- The X axis frequency weighting is more shallow than the standardised frequency weighting by about 2 dB per octave throughout the entire range investigated.
- The Y axis frequency weighting has approximately the same slope as the standardised frequency weighting.
- The Z axis frequency weighting is much steeper than the standardised frequency weighting in the very low frequency range, where it drops by about 10 dB per octave (that has to be compared with flat standardised weighting). In the mid-frequency range, the Z frequency weighting is still slightly steeper than the standardised frequency weighting by about 1,2 dB per octave, until about 125 Hz. Beyond this point the curve becomes less steep, by approximately the same amount.

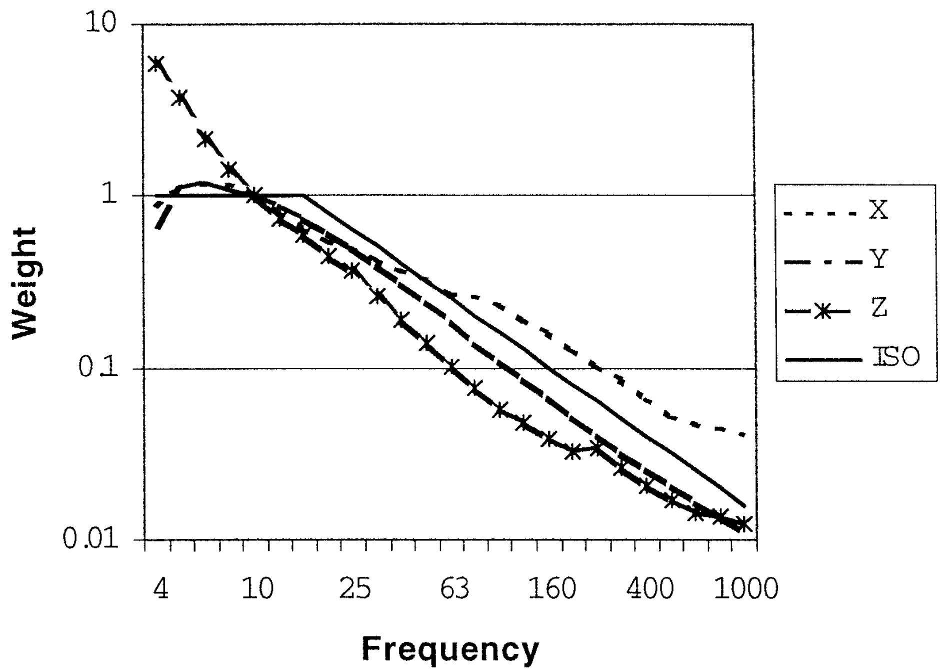

Figure 1 : Comparison of standardised weighting curve and equal absorbed power.

2.3. Frequency weighting based on physiological measurements

2.3.1. Neurological disorders

Measurements of vibrotactile perception thresholds at the fingertip may be used to assess the tactile performance of the fingers. Significant persistent threshold shifts may be related to peripheral neuropathies in the upper extremities (ISO pr 13091). Exposure to vibration results in an increase in vibration perception threshold followed by a recovery of perception lasting 10 min. or more (Amaral, 1999). Experiments were made to evaluate the difference in percent between the threshold before and after the exposure. The effect of vibration with different frequencies may be compared and a frequency equivalent curve could be deduced.

Nishiyama and Watanabe (1981) investigated the relationship between the temporary threshold shift of vibration sensation at 125 Hz after clasping a vibrating handle and the frequency and acceleration of the handle vibration. They found that the temporary threshold shift after exposure to the 250 Hz vibration was significantly the largest in all frequencies at equal acceleration.

It has been found by Maeda and Griffin (1993) differences in temporary threshold shift (TTS) in vibrotactile perception after exposure during five minutes to repetitive shocks with the same frequency weighted rms levels but with different rates of shock repetition. They used one period of 100 Hz as the shock and repeated it 5, 25, 50 and 100 times per second. The TTS, measured at the fingertip with a stimulus of 125 Hz, increased with shock repetition frequency, the highest being found at 100 Hz over the frequency range.

Kihlberg et al (1995) exposed subjects to 3 min. of vibration emitted by a grinder and a chipping hammer with the same frequency weighted acceleration. They compare various effects on the hand arm system : muscle activity, discomfort ratings and vibration perception threshold. They found a higher threshold shift after the grinder exposure (at 137 Hz) than after the chipping hammer exposure (at 50 Hz) with a testing frequency of 100 Hz. They concluded that their results do not support the notion that one single frequency weighted curve would be valid for the different health effects of the hand arm vibration (vascular, musculoskeletal, neurological, and psycho physiological).

In the same way Amaral (1998), Malchaire et al (1998) compared shift of TTS for stimuli of 31.5 and 125 Hz after the exposure of operators to 31.5, 125 and 500 Hz vibration. They noted that the TTS increases with the logarithm of vibration acceleration magnitude. They also showed that the shift of TTS is greater at 125 Hz than for 31.5 Hz and 500 Hz. This is in contradiction with the ENV 25349 frequency weighting (see Table 1). A new weighting curve more appropriate to the assessment of neurological disorders could be derived from experiments based on the measurements of TTS. However Amaral results show differences between conditions of tests. It is known that different test stimulus frequencies will elicit responses from different mechanical receptors. The shape of a weighting curve may depend on the type of receptor activated.

Test frequency (Hz)		Vibration exposure frequency (Hz)		
		31.5	125	500
31.5	measured	0	+ 1.4	- 1.1
	ISO 5349	0	- 4.8	- 9.6
125	measured	0	+ 6.9	- 0.3
	ISO 5349	0	- 8.5	-17

Table 1: Comparison of TTS differences in dB measured and calculated using standardised weighting curves (from Amaral, 1998).

This was clearly shown by Harada and Griffin (1991) who exposed five subjects to vibration at 20 m/s^2 rms from 16 to 500 Hz at octave band intervals. Vibration sense thresholds were measured before exposure and after 30 seconds. Figure 2a shows the temporary threshold shift as a function of exposure frequency for each threshold test frequency and compared with the controls, in which subjects grasped the handle but were not exposed to vibration. The TTS of vibration sense at 16 Hz and 31,5 Hz was highest after exposure to lower frequencies of vibration, such as 16 Hz and 31,5 Hz. The TTS of vibration sense at 63 Hz was almost the same after exposures to all frequencies. The TTS of vibration sense at higher frequencies such as 125 Hz, 250 Hz and 500 Hz was highest after vibration exposure of 125 Hz and 250 Hz. Figure 2b gives another representation of the results of TTS. Vibration sense thresholds are shown as a function of exposure frequency for each threshold test frequency. The TTS of the vibration sense at the higher test frequencies, such as 125 Hz, 250 Hz and 500 Hz, was apparently different from those at lower frequencies such as 16 Hz and 31,5 Hz. The effect on the TTS at 63 Hz was between the effects at higher and lower frequencies. These data indicate that maximal TTS may be induced in the FAI and FAII units by exposure to vibration at different frequencies.

Assuming that a frequency weighting curve could be derived from TTS to protect operators from neurological disorders, these results speak more in favour of a flat weighting curve than the present sloppy curve recommended by ENV 25349.

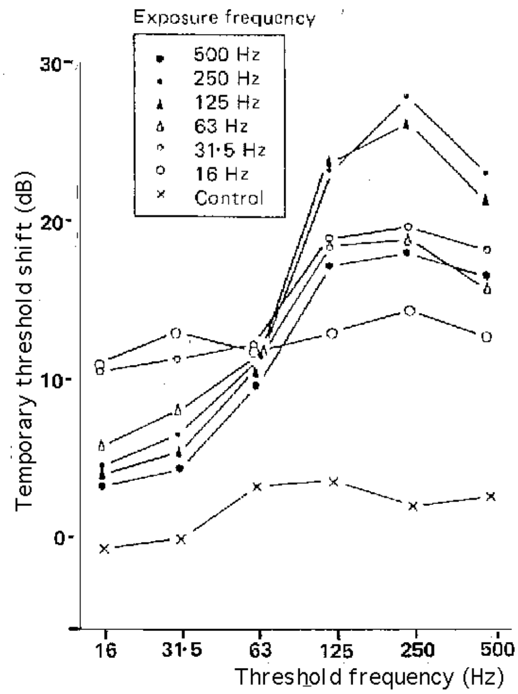

Figure 2a : TTS of the vibration sense of the fingertip induced by exposure of the hand to vibration of 20 m/s^2 rms according to Harada and Griffin (1991). Effect of threshold frequency.

The temporary threshold shift of temperature sensation due to vibration exposure was studied by Hirosawa et al (1992) to clarify the effect of frequency (from 32 to 500 Hz) and acceleration (from 2 to 16 g) on it. The threshold shift of warm sensation (TTSw) was markedly, but that of cool sensation was small and not significantly different from the control value. TTSw increased with the level of acceleration and was largest at 125 Hz. The most effective frequency among the vibrations tested for warm sensation was inferred to be lower than that for vibration sensation.

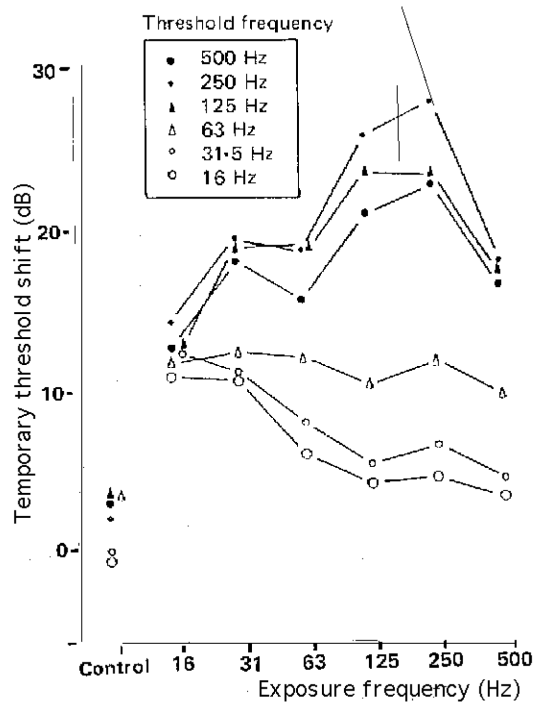

Figure 2b : TTS of the vibration sense of the fingertip induced by exposure of the hand to vibration of 20 m/s^2 rms according to Harada and Griffin (1991). Effect of exposure frequency.

2.3.2. Vascular disorders

After reviewing published data (Furuta et al, 1991 ; Kent et al, 1991 ; Hyvärinen et al, 1973 ; Welsh, 1980 ; Nohara et al, 1986 ; Färkillä and Pyykkö, 1979) on vibration and finger blood circulation, Bovenzi and Griffin (1998) came to the conclusion that there is no firm evidence for an increase in the magnitude of vibration acceleration required to provoke digital vasoconstriction as the vibration frequency increases. Despite the sparseness of data and the differences in experimental procedures, the various studies tend to indicate that, at constant acceleration magnitudes, vibration frequencies from 30 to 500 Hz can consistently affect digital circulation in both healthy subjects and patients with Raynaud's phenomenon. Within this frequency range, there is some evidence that the frequency of 125 Hz is more effective in inducing digital vasopasm than either lower or higher frequencies. These findings are also supported by the results of pathological studies showing that vibration of 30, 60, and 480 Hz at 50 m/s^2 caused comparable pathohistological changes in the peripheral arteries of experimental animals. Therefore the use of the standardised frequency weighting curve may overestimate risk for low frequency vibration.

Bovenzi and Griffin (1998) carried out an experiment where they measured the finger skin temperature, finger blood flow and finger systolic pressure in the fingers of both hands in eight healthy men. They found that exposure to vibration of 125 Hz and 22 m/s^2 produced a greater reduction in finger blood flow and a greater increase in vasomotor tone that did vibration of 31,5 Hz and 22 m/s^2.

Bovenzi et al (1999-1) showed that acute exposure to 125 Hz vibration magnitudes greater than 22 m/s^2 can reduce finger blow flow in both the vibrated and the non vibrated finger. The higher the vibration magnitude, the stronger the reduction of finger blow flow in either finger during both vibration exposure and the recovery period.

Bovenzi et al (1999-2) evaluated the appropriateness of the ENV 25349 weighting curve to predict vascular disorders. The indices of circulatory function (such as finger skin temperature, finger systolic blood pressure, etc.) were measured before, during and after exposure to different sinusoidal vibration stimuli from 16 to 250 Hz with the same frequency-weighted rms acceleration (5.5 m/s^2). They concluded that acute exposures to vibration with equal frequency-weighted magnitude reduce the finger blow flow in both vibrated and non vibrated fingers for frequencies between 31.5 and 250 Hz. The extent of digital vasoconstriction following vibration exposure increases with increasing frequency. The frequency weighting given in current standards tends to overestimate the vasoconstriction associated with acute exposures to vibration frequencies around 16 Hz (figure 3).

In addition Bovenzi et al (1998) showed that not only the frequency and magnitude of vibration, but also its duration contributes to the reaction of the digital vessels to acute vibration. In a more recent paper (2001) they show that the eight hour “energy equivalent” frequency weighted acceleration according to ENV 5349 failed to predict these effects.

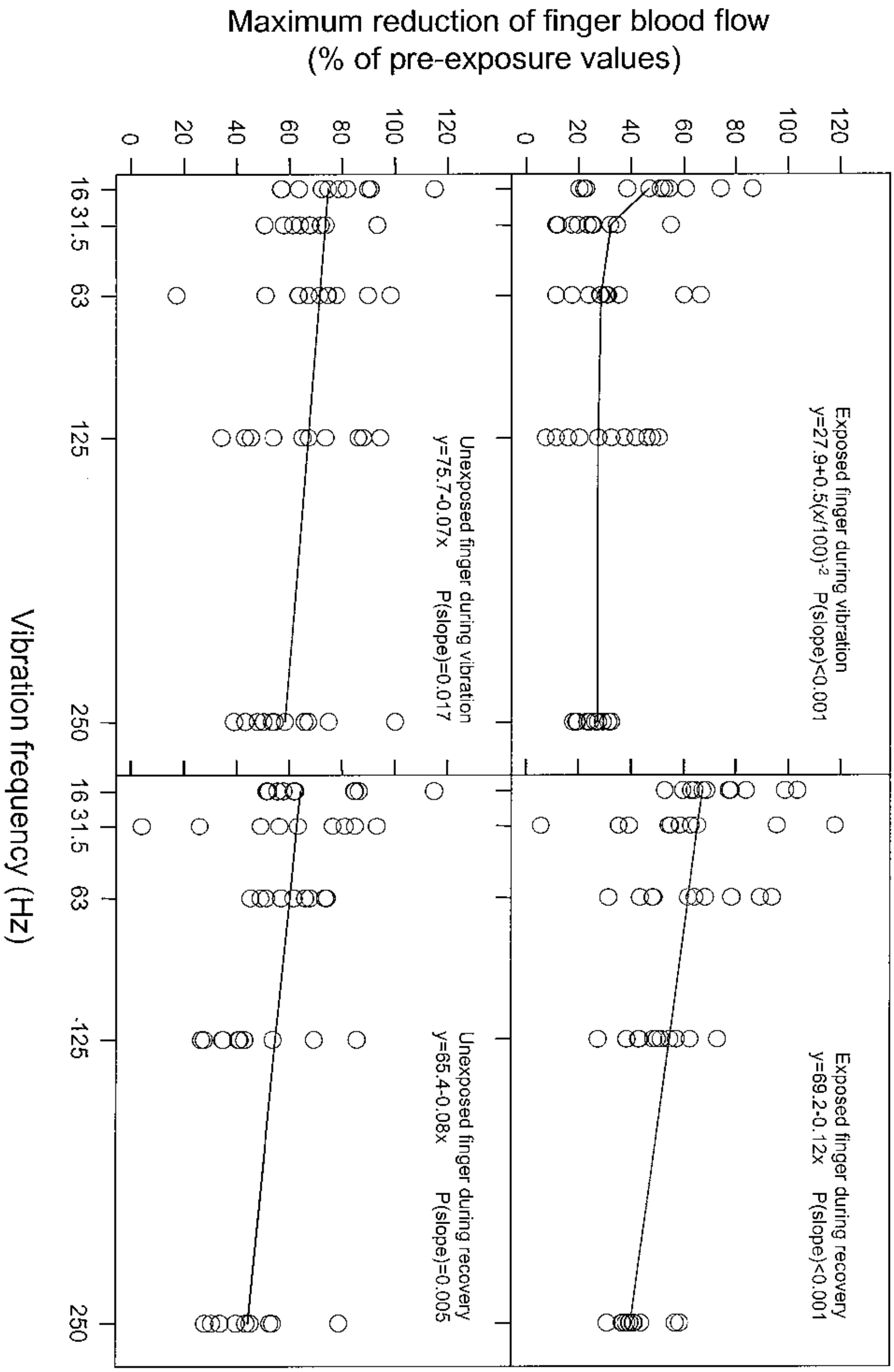

Figure 3 : Effects of vibration frequency on the maximum reduction of finger blood flow (expressed as a percentage of the pre-exposure values) during and 45 min after exposure to vibration with a frequency-weighted acceleration of 5.5 m/s^2 r.m.s. According to Bovenzi et al (1999-2).

2.4. Frequency weighting based on epidemiological research

In an epidemiological study of dockyard workers Nelson and Griffin (1993) found that the occurrence of vibration white fingers and its severity fit better with measures of vibration dose including unweighted acceleration rather than acceleration frequency weighted according to ENV 25349. They considered that the standardised frequency weighting placed insufficient importance on some of the higher frequencies.

Tominaga (2001) studied 13 groups of about 20 users who had mainly worked with one of the five different percussive tools: chipping hammer, jack hammer, large and small sand rammer, rock drill hammer. It compares the relationship between vibration exposure and the prevalence of complaints of vibration-induced white finger, finger numbness and pain in elbow/shoulder. The prediction obtained with the standardised weighting curve did not fit with the observed prevalence of effects. Therefore he tried to optimise these relations by using suitable frequency weightings deduced by the method of the least square error for each class of complaints. Figure 4 shows the best fit curves for the three classes of complaints. According to Tominaga mid and high frequency components of the vibration would tend to effect numbness and VWF effects while elbow/shoulder disorders would be associated to low frequency components. Different weighting curves should be used according to the class of complaints.

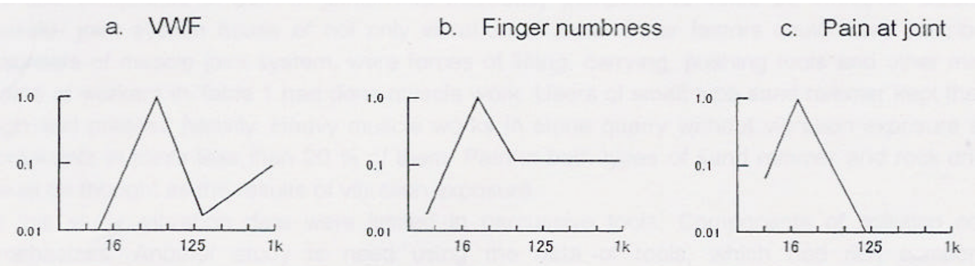

Figure 4 : Best fit frequency weighting curves according to the class of complaints. According to Tominaga (2001)

3. Validity of estimates of duration of exposures

3.1. Review of standardisation

The assessment of daily exposure duration must be made to calculate the vibration exposure which it is based on the measurement of the actual exposure time of tool normal use during a complete work cycle or a typical period multiplied by the work rate such as the number of cycles per day. Many publications give information on how the vibration acceleration was measured. On the other hand they are generally silent on the difficulty to estimate the exposure duration. The draft standard EN 25349-2 is to our knowledge the only document which deals this problem in details as summarised below.

The assessment of the actual exposure time is generally measured, using a stopwatch, analysis of video recordings or activity sampling techniques to determine how long an operator is exposed to vibration, and from what source, during a specified period.

The most reliable source of information on typical work rate is work records. However, it is important to ensure that the information is compatible with the information required for an assessment of daily vibration exposure. For example, work records might give very accurate information on the number of completed work items at the end of each day, but where there is more than one operator, or unfinished work items at the end of a shift this information may not be directly applicable to a vibration exposure assessment.

The accuracy of the estimation of exposure time is affected by the accuracy of :

- measurements of the durations of exposure,
- estimates of the number of working cycles per day,
- exposure time estimates supplied by the operators. This may come from misinterpretation of the question (confusion between usage of the tool and real exposure to vibration), as well as poor estimates of the durations for which exposure to vibration occurs.

The operators tend to overestimate the duration (they will normally give an estimate of the period of time for which a tool is hold, including pauses in operation). Estimates of usage time, which include breaks in tool operation, may be used provided that the vibration measurements are made over equivalent periods.

Moreover the amount of time using vibrating tools may be highly variable from one day to the next ; in this case the assessment may be based on weekly or monthly estimates and an equivalent daily exposure deduced by calculation.

3.2. Tentative to evaluate the validity of estimates of exposure durations

The exposure durations of one hundred and sixteen operators using hand-powered tools were directly measured by Palmer et al. (1999) over a one hour period during representative activities. Among them 69 people used a single tool, 31 used two tools, 8 used three and 5 used five. Separately each worker was asked to complete a postal questionnaire providing details of occupation and hand-powered vibration tools used in the previous week. Figure 5 compares the reported exposure times with the time observed. The plot illustrates the strong general tendency to over-report exposure times ; the wide scatter of reported times for similar periods of true exposure ; and the evident tendency to round estimates up or down to the nearest whole multiple of five or ten minutes.

The exposure durations of 55 workers employed in the aircraft industry were evaluated by INRS from direct observation (time do drill a hole or to polish an aluminium component) and exact number of holes, rivets or components daily made (this data is obtained from head staff who knew exactly the number of holes, rivets, etc. to prepare a given aircraft part, the number of operators doing the task and the number of days needed). Separately the workers were asked by different experimentators to fill a medical questionnaire and to report about exposure durations. The results confirm the tendency of employees to over evaluate the exposure durations mainly because they generally give an estimate of the period of time for which a tool is hold, including pauses in operation. In the case of people using rivets and drillers the average ratio was about 10 to 1. In the case of people grinding or polishing components the ratio was on average 3 to 1. These values depend on the working site. A similar work was done in a foundry with operators using grinders and chipping hammers. The work rate was far higher (in the aircraft industry people are asked to take their time because perfection is a necessity). In foundry the ratio was 3 to 2.

Lenzuni (1998) performed an enquiry on users of rock drilling hammers in a dozen of quarries. Workers have indicated their exposure times while interviewed by a team of physicians. Employers have indicated exposure times in the risk evaluation document they must prepare according to the Italian law. Figure 6 shows the histogram of the ratios of durations reported by workers versus durations reported by employers. Most of the time the duration of exposure is "under evaluated" by the employers or "over evaluated" by the employees (see Palmer results above).

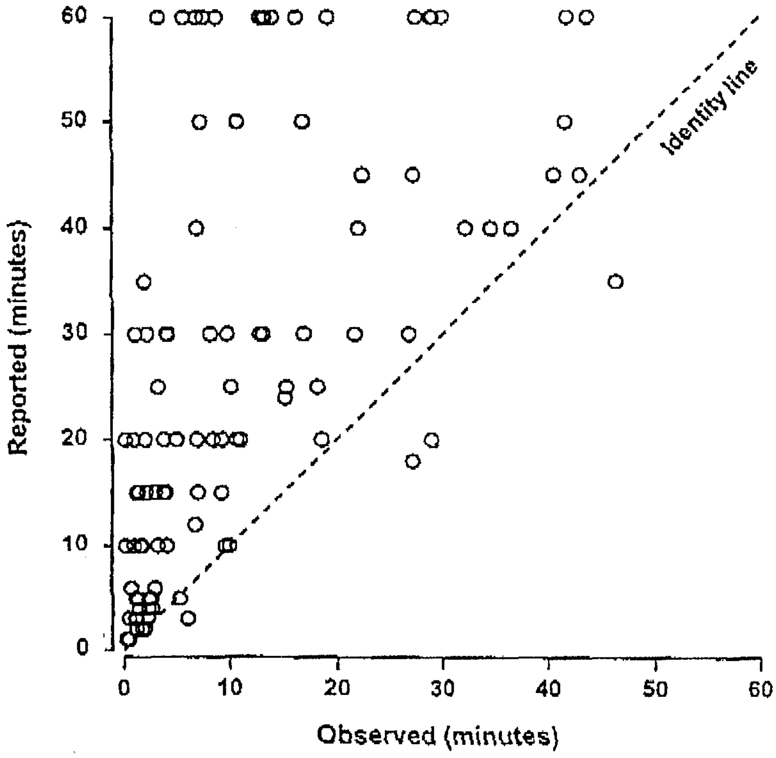

Figure 5 : Reported versus observed exposure times (from Palmer, 1999).

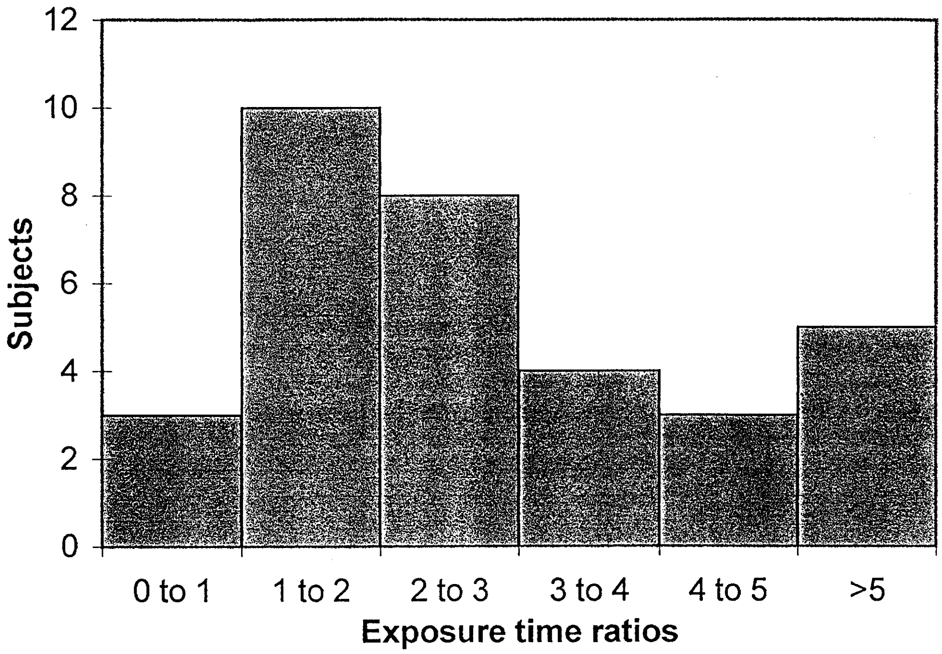

Figure 6 : Ratios of durations reported by workers versus durations reported by employers. Case of workers exposed more than 30 min according to employers (communication from Lenzuni, 1998).

4. Conclusions

<u>Frequency weighting curve</u> : The effect of the present shape of the frequency weighting recommended by the ENV 25349 and pr ISO 5349-1 is huge on the vibration exposure value calculated as recommended by standards. However there is strong doubt about this shape. The National Institute for Occupational Safety and Health (NIOSH) proposes the use of unweighted acceleration to assess vibration exposure and health risk in the United States (1989).

Research results do not support the notion that one single frequency-weighting curve could be valid for the different health effects on hand-arm vibration (Kihlberg et al, 1995). However there are difficulties to find objective tests which may be used to develop specific weighting curves. As a matter of fact these tests shall be connected to the health effect studied but also they should give values which are independent of the characteristics of the test itself.

The Machinery Directive encourages tool manufacturers to design low vibration tools. They are asked to declare the vibration emitted to enable buyers to compare tool severity. One way of reducing the weighted rms acceleration is to increase the frequency content of vibration by increasing the blow rate of percussive tool or the speed of a rotative machine. Are these tools safer ? Waiting for more results we recommend not only to reduce the weighted rms acceleration of the emitted vibration but also the unweighted rms value.

ISO/TC108/SC4 has decided in June 1999 to introduce a new preliminary work item on frequency weighting characteristics for hand-transmitted vibration in its programme of work. An ad hoc group of WG3 should gather data to provide evidence for revision of the frequency weighting of pr ISO 5349-1 in the long term.

<u>Exposure durations</u> : Experiments show that the operators cannot be trust to evaluate their exposure durations. They tend significantly to overestimate the duration of hand-arm vibration exposure because they generally give an estimate of the period of time for which a tool is hold, including pauses in operation. Correct assessment of durations should be done through direct observation of operation and deduced from knowledge of number of daily work cycles. Unfortunately the amount of time using vibrating tools may be highly variable from one day to the next.

6. Acknowledgements

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