EVALUATION OF HUMAN EXPOSURE TO HAND-TRANSMITTED VIBRATION

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ABSTRACT

The relative importance of some of the parameters instrumental in producing vibration induced white finger (VWF) has been identified. Difficulties encountered in measuring the vibration signal and possible means of overcoming them are discussed. The problems of setting up a damage risk criteria are considered, and reference is made to a number of proposed criteria.

Particular reference has been made to the relevance of a new draft British Standard and the way in which it deals with a number of spectra relating to different work processes known to cause VWF.

INTRODUCTION

Although the problem of vibration induced white finger (VWF) among users of hand-held vibrating tools has been well known for a number of years, only relatively recently has much attention been paid to measuring the vibration stimulus. At the first International Conference on Hand-Arm Vibration, in Dundee in 1972, there was only one paper that attempted to relate the measured vibration characteristics of the processes that caused VWF to the incidence of the complaint. Today a number of workers are attempting to measure the vibration and the hope is that, despite the problems encountered in making the measurements, it will be possible to recommend reliable safe working limits.

Agate and Druett[1] were among the first to suggest that frequencies in the range 40 to 125 Hz were most instrumental in the production of VWF. However, they did not suggest any vibration levels that would be indicative of potential hazard. It should be hoped that Agate and Druett's work could be improved upon, both in terms of accuracy and range of parameters to be considered, and that we should be encouraged in our search for a dose-response relationship.

VIBRATION MEASUREMENT

It is clear that the movement of the hand-arm system when subjected to vibration is complex and difficult to characterize. At the present time, the search for the specification of safe working limits is proceeding by measuring the vibration of the object that is grasped by the hand. The question of the energy transfer into the hand is left unanswered for the moment and is a matter for further research.

The measurements are taken in three mutually perpendicular directions by fixing an accelerometer to the vibrating surface. This gives a voltage output that is proportional to the acceleration of the object. The choice of acceleration is usually made because it is the parameter that can be measured both simply and directly and is also immediately related to the force exerted on the hand.

The vibration, in general, must be considered as a random process that therefore produces a random signal. To specify the magnitude of such a signal, it is necessary to perform a time average over as long a time as possible. The most usual way of doing this is to specify the root mean square (RMS) value. To obtain information about the frequency content, the signal is passed through a band pass filter of width Δf and center frequency f. This can give the power spectral density function

$$G(f) = \lim_{\Delta f \to 0} \frac{1}{\Delta f} \left[\lim_{T \to \infty} \frac{1}{T} \int_{t}^{t+T} x^2 \; (f, \Delta f) \; dt \right] \quad (1)$$

where x is the instantaneous value of the signal. In practice, we use either octave or $\frac{1}{3}$-octave bands, where $\Delta f = 0.7 f$ and $0.22 f$, respectively, to specify the frequency content of the signal. The RMS acceleration A within a specified bandwidth is related to $G(f)$ by:

$$A = \left[\int_{f_1}^{f_2} G(f) df \right]^{\frac{1}{2}} \quad (2)$$

All the spectra to be presented in this paper show RMS accelerations as a function of third octave or octave band center frequency. When averaging is done for a finite time, T, the accuracy of the RMS value is related to T and Δf. The relative error being given by

$$e = \frac{1}{2(\Delta f \cdot T)^{1/2}}$$

It is clear, therefore, that for octave band analysis at low frequencies where Δf is small, the error will be high unless T is large. This can be particularly difficult with signals of short duration of the kind associated with many processes that produce VWF (e.g., the use of chain saws and grinders).

Other points of detail that need particular attention in the measurement of vibration are:

1. The choice and mounting of the accelerometer are critical to achieve a flat frequency response over the range of interest. With impulsive tools, such as pneumatic hammers, repeated shock pulses with very high peak acceleration levels can occur. These can cause the DC level on the output from the accelerometer to change, and the change can result in difficulties in the subsequent analysis. In these circumstances it may be necessary to place a resilient pad between the work piece and the accelerometer. This behaves as a low pass mechanical filter and prevents the very high peaks from disturbing the accelerometer.
2. The dynamic range of the instrumentation is usually limited by the use of a tape recorder. For signals with high acceleration levels at high frequencies, the required dynamic range can be reduced either by using a low pass filter in the preamplifier to eliminate the effects of exciting the accelerometer resonant frequency, or by using an integrator to measure the velocity component of the vibration.
3. The manner in which the operator holds the workpiece is probably a factor of considerable importance and undoubtedly affects the measured vibration levels. The quantification of this effect is difficult, and for the present, it is suggested that the workman hold the workpiece in as normal a manner as possible.

GUIDELINES FOR SAFE EXPOSURE LIMITS

A number of proposals recommend safe exposure limits, but none of these can be said to represent reliable damage risk criteria. Figure 1 shows six of these suggestions. Each curve is intended to indicate maximum vibration levels for continuous daily exposure. Clearly the variation between them is so great that application of any one of them should be performed with caution, particularly as the basis for the proposals is almost entirely that of subjective assessment of what vibration levels are "noticeable," "unpleasant," "intolerable," etc.

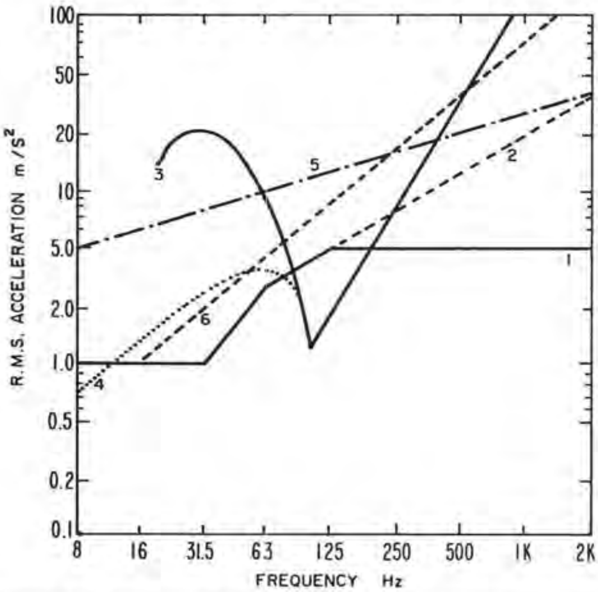

Figure 1. Maximum vibration levels for continuous daily exposure: 1) Czechoslovakian Hygiene Regulation No. 33; 2) Teisinger and Louda, Czechoslovakia 1966; 3) USSR Hygiene Regulation 1955; 4) USSR Gataninas Proposal after 1955; 5) USSR Hygiene Regulation 1966; 6) Draft British Standard 1975 400 minutes per day.

The International Standards Organization (ISO) has been working towards the development of a set of guidelines that would have a wide measure of acceptance. In Figure 2, the most recent set of propos-

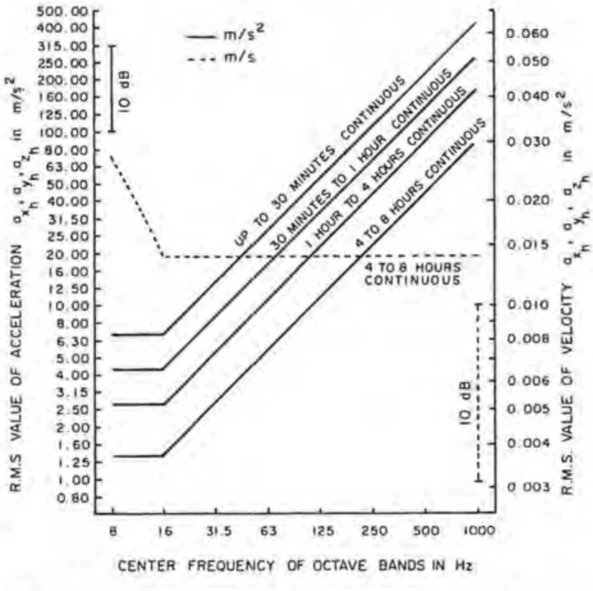

Figure 2. Tentative exposure limit curves. ISO 1975.

als are summarized.[2] Recommended limits are quoted for both velocity and acceleration measurements made in either octave or ⅓-octave bands and are intended to be applied to each axis of measurement separately. Medical and epidemiological data that can be cited in support of these proposals are limited, and the suggested limits are a consensus based on practical experience and laboratory experimentation in the field of human response to hand transmitted vibration.

Some attempt is made in the ISO proposals to allow for exposure durations of less than a full day. The correction factors that need to be applied for exposure durations of less than 8 hours are given in Table 1. Some workers believe that regular interruption of exposure can be beneficial,[3] and the correction factors to be applied for different total daily exposures when the vibration is regularly interrupted during a daily shift are given in Table 2.

Table 1. Correction factors for total daily exposure times of less than 8 hours, uninterrupted or not regularly interrupted

Exposure time during daily shift (8 hours)	Correction factor
Up to 30 minutes	5
30 minutes to 1 hour	3
1 to 4 hours	2
4 to 8 hours*	1

*The 4- to 8-hour exposure limits shall be raised by the correction factor.

Table 2. Correction factors for regularly interrupted vibration exposures during daily shift

Duration of time interval without vibrations per working hour	Daily exposure times	
	1 to 4 hr	4 to 8 hr
2 to 10 minutes	1	1
10 to 20 minutes	2	1
20 to 30 minutes	4	2
30 to 40 minutes	5	3
40 minutes or more	5	5

It could be argued that the lack of good medical and epidemiological data makes it difficult to accept the degree of precision that might be inferred from these correction factors. Furthermore, as accuracy of vibration measurement still presents a problem, it is probable that any interpretation of the ISO proposals should not be taken too literally.

In the United Kingdom, a more flexible approach has been adopted, where only the total duration of exposure to vibration is regarded as important and any interruptions or irregularities in the exposure are not quantified in any way. In Figure 3 are the two curves that form the basis of the recommended exposure limits from the British Standards Draft for Development.[4] The 400-minute curve is the recommended limit for continuous daily exposure and the 150-minute curve is the proposed limit for interrupted

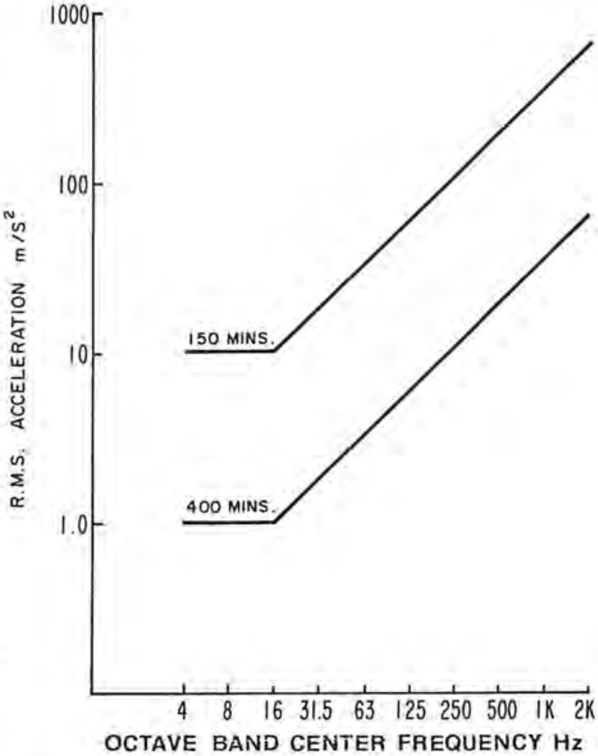

Figure 3. Recommended exposure limit curves - British Draft for Development 1975.

daily exposure for any vibration repeated regularly. No vibration repeated regularly should exceed the 150-minute curve. For exposure durations between 150 and 400 minutes, it is proposed that interpolation between the two curves be performed. It can be seen that the curves are the same shape as those in the ISO proposals but are set at slightly different levels. Clearly, the difference in approach can cause anomalies to occur, e.g., an exposure pattern composed of 4 minutes of vibration followed by a 6-minute break, regularly interrupted, for 3 hours would require a correction factor of 5 according to the ISO recommendations. If the same total exposure duration occurred without the interruption being regular, the correction factor would be 2. The U.K. proposal would suggest a correction factor of 10 on its own 400-minute exposure curve.

Obviously, it is not possible at the present time to resolve which, if either, of these two approaches is more accurate. It is often suggested, however, that the assessment of risk would be easier to evaluate if the energy input into the hand were measured rather than the vibration on the tool itself. Implicit in this suggestion is an assumption that equal amounts of energy cause equal amounts of damage. Clearly, there can be situations where current proposals for recommended exposure limits are at considerable odds with an equal energy principle.

This lack of general agreement on the principle upon which any proposals are to be applied makes evaluation of mixed exposures impossible; e.g., the exposure to more than one period of vibration may be such that any one of them, taken separately, may be acceptable, but taken together, the exposure may be unacceptable. Existing proposals do not indicate how this difficulty can be resolved. Indeed, it may well be impossible to resolve it until much more medical and epidemiological data have been collected.

It is clear, therefore, that, at present, there is not much point in debating which of the existing proposals is the more appropriate, but we should accept them for what they are—that is, tentative recommendations that should be regarded as offering "provisional guidelines," rather than definite damage risk criteria.

Nevertheless, whatever their limitations, it is clearly of interest to examine if there are any data that will validate the proposals. Unfortunately, not a great deal of suitable data is available. Although we do have a limited amount of information relating to measured vibration levels, there are very few data giving details of exposure patterns in specific work situations. For this reason, comparing recorded data with the ISO proposals is rather difficult. For the purposes of this presentation, then, how some vibration information compares with the recommendations of the draft British Standard will be examined.

ASSESSMENT OF DRAFT BRITISH STANDARD

Although measurements are made in three directions, in practice there are usually no gross differences between the three spectra and, therefore, in this paper results are quoted for one direction only.

Chain Saws

Several designs of saw, including saws with and without anti-vibration mountings have been studied. In Figure 4 are typical spectra recorded on the rear handle of both types of saw. (In general, the vibration levels tended to be higher on the rear handle than those on the front handle.) Also shown on the figure are the curves from the draft British Standard.

Studies of forest working techniques have indicated

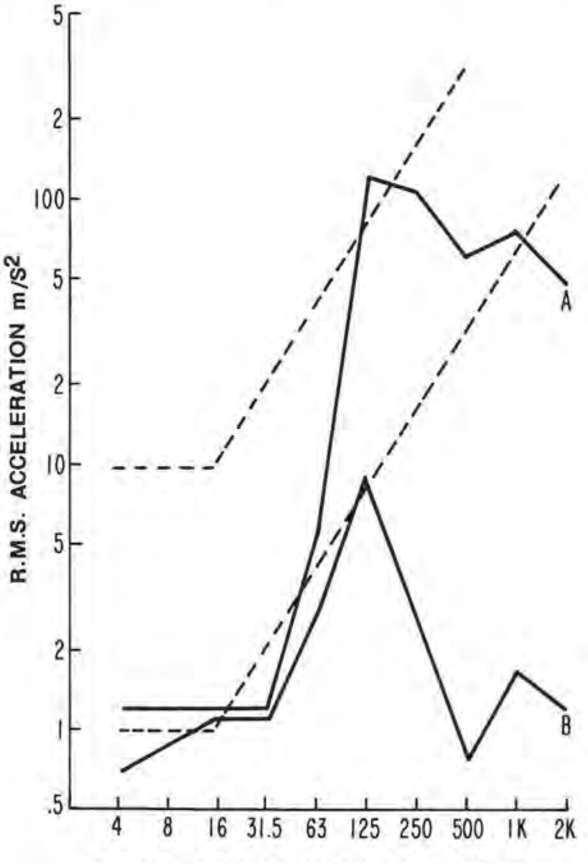

Figure 4. Comparison of chain saw spectra with the proposals of the Draft British Standard A: no anti-vibration mounting, B: with anti-vibration mounting.

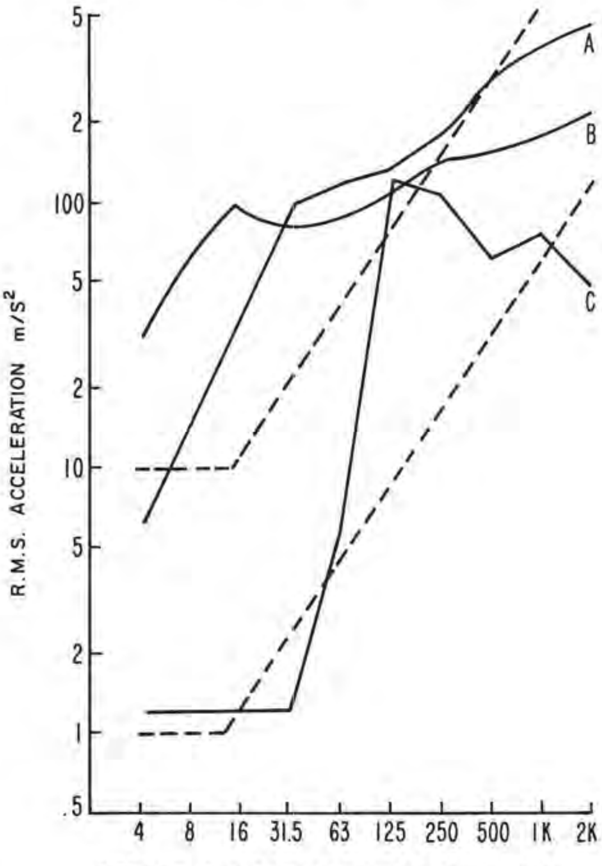

Figure 5. Comparison of swaging, grinding, and chain saw spectra with the proposals of the Draft British Standard. A: swaging, B: grinding, C: chain saw.

that the saw is actually being operated for between 150 and 270 minutes during a typical 8-hour working day. Before the introduction of anti-vibration saws, VWF symptoms began to appear in saw operators after a latent period of about 3 years. The subsequent introduction of anti-vibration saws brought about a considerable improvement in the incidence of VWF. From the curves in Figure 3, it might be suggested that for a 270-minute daily exposure, the anti-vibration saw would be satisfactory whereas the non-anti-vibration saw would not. Because of the nature of the spectra, this evaluation is largely based on the levels of vibration in the region of the 125 Hz octave band. Clearly, these spectra offer little evidence in support of the proposals outside this range of frequencies, in particular, those below 100 Hz.

Grinders and Swaging

Spectra obtained from grinders used for removing excess metal from castings vary considerably because of factors such as the size and shape of the casting, the type of grindstone, and the eccentricity of the grinding wheel surface. Recently, harder and longer wearing grindstone wheels have become available, and these wheels have been thought to be instrumental in the increase of VWF among people who use them. Figure 5 shows a typical spectrum obtained when a 200-mm-diameter casting is being ground on one of these harder wheels, together with a spectrum obtained when a process known as swaging is performed. During swaging, a man holds a pipe in a machine that reduces its diameter over a short distance at one end. Comparison of these two spectra with those of the non-anti-vibration chain saw in Figure 3 indicates that the levels are all similar in the region of the 125 Hz octave band, whereas considerable differences occur below 100 Hz. The latent periods for operators of the chain saw, the grinder, and the swaging machine, are approximately 3 years, 1.8 years, and 0.6 years, respectively. Exposure times might be expected to be similar for all three processes, and therefore, the position of the draft standard curves indicates the possible dangers of some of the frequencies below 100 Hz.

Pneumatic Tools

Measurement of vibration on pneumatic tools can present particular difficulties. In Figure 6 are three

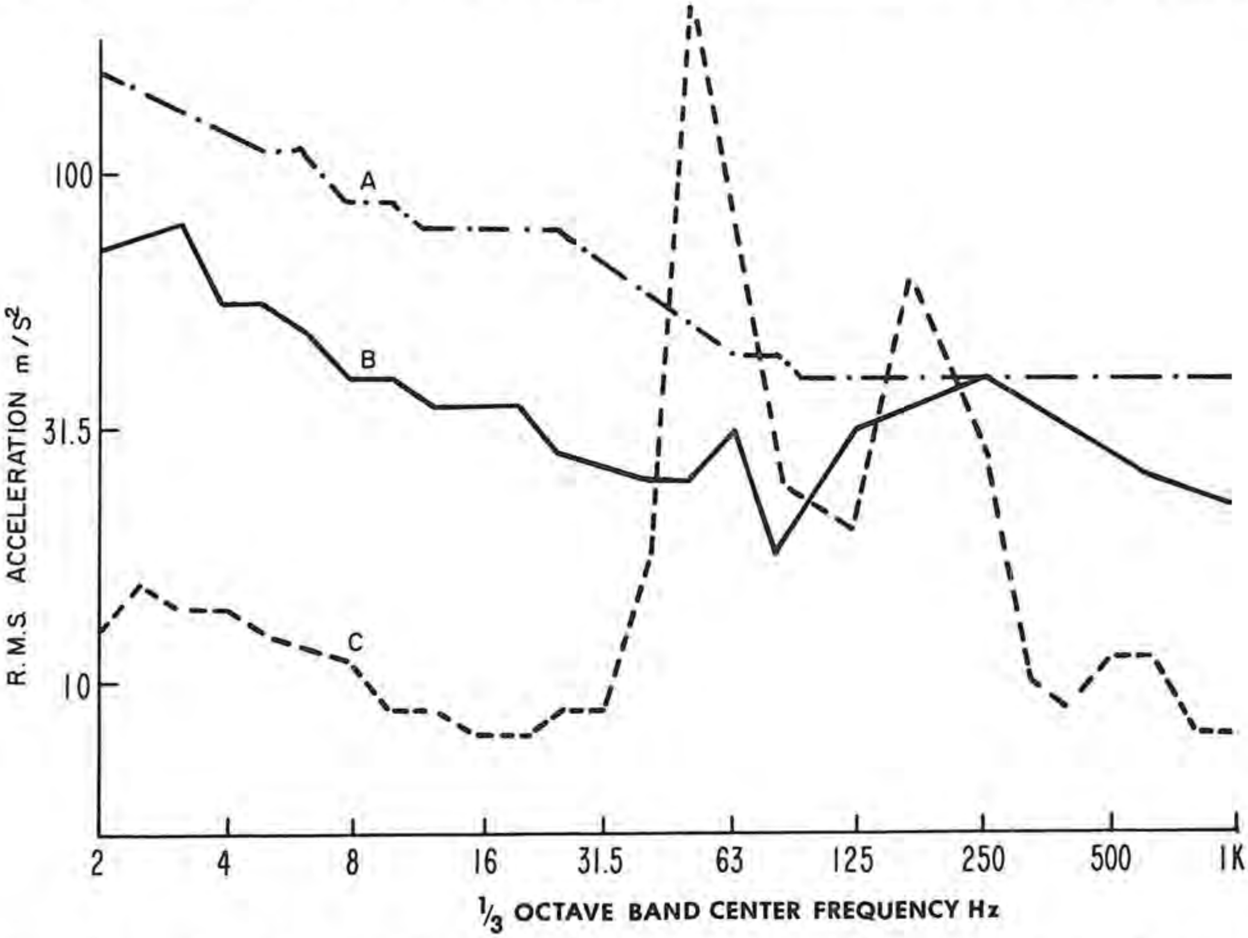

Figure 6. One-third octave analysis from pneumatic scaling hammer, A and B: accelerometer on head, C: accelerometer on the handle.

spectra that were recorded on the same pneumatic paint remover or "nobbler." Spectra "A" and "B" were measured on the head of the instrument and "C" on the handle. Although the levels on the head appear to be higher, they are in fact somewhat misleading, e.g., the measured levels at 4 Hz are equivalent to a peak-to-peak displacement of about 4.5 m. Clearly, this cannot be correct, and what, in fact, has happened is that the DC shifts, referred to earlier, have produced an inaccurate spectrum when the output from the accelerometer has been analyzed. Lack of awareness of this problem can obviously give rise to an erroneous assessment of the tool.

Figure 7 shows a more meaningful spectrum from

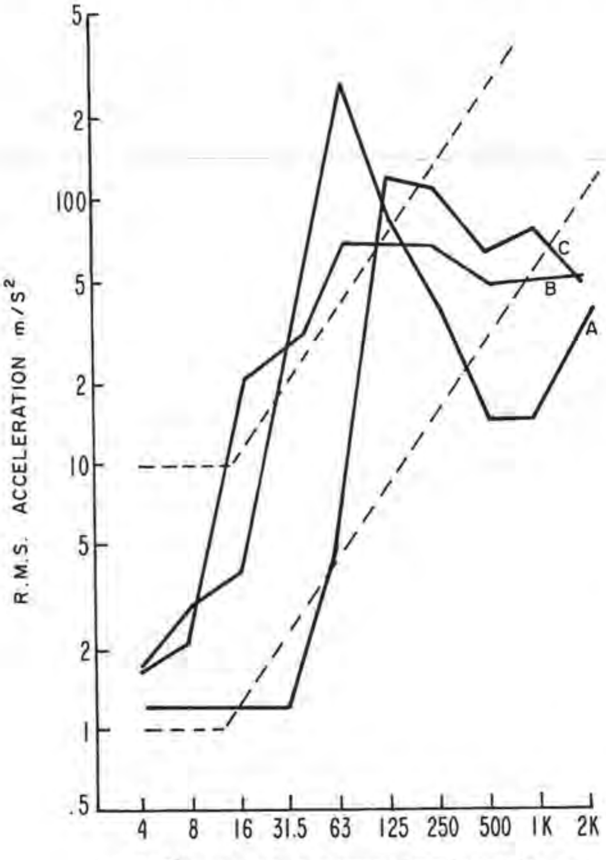

Figure 7. Comparison of pneumatic paint remover (nobbler), road breaker and chain saw spectra with the proposals of the Draft British Standard A: paint remover, B: road breaker, C: chain saw.

the paint remover (nobbler, curve A) together with that from a road breaker (B) and that from the non-anti-vibration chain saw (C). It appears that the incidence of VWF associated with the use of the nobbler and the road breaker is less than that associated with the chain saw. The use of the paint remover and road breaker involve complex work patterns, thus making the assessment of total exposure rather difficut. The level of vibration in the spectra from both tools exceeds the 150-minute curve, over a range of frequencies below 100 Hz. This observation apparently conflicts with the observed low incidence of VWF in operators who use the tools. Clearly, much more detailed information on exposure patterns is necessary. The effects of rest periods, the period of time during which the tool is idling, and the duration and number of interruptions of the exposure that occur during a shift are factors whose importance has to be assessed.

At present, however, the proposed curves seem to be reasonable in that levels that exceed them are likely to be hazardous and there have been no instances reported of a known hazardous vibration that lies entirely below the 400-minute curve. Nevertheless, the evidence so far available is far from complete, and it is clear that more information is needed on the relative importance of different ranges of frequencies in the production of VWF.

WEIGHTED VIBRATION LEVEL

It is interesting to postulate upon the possibility of there being a single figure reading of the vibration magnitude, rather like the dB(A) in noise, that will predict the hazard. By introducing a weighting network with a response, which is the inverse of the recommended exposure limit curves, into the frequency response of the measuring equipment, it is possible to express the vibration in terms of a single figure that will indicate the amount by which a spectrum exceeds the proposed exposure limit curve. A broad band spectrum that followed the 150-minute curve would have a weighted reading of 31.5 m/s^2; one that followed the 400-minute curve would read 3.15 m/s^2. If, however, a spectrum is concentrated in a very narrow range of frequencies, these weighted levels may not be strict enough. Pneumatic tools and chain saws often have spectra where the level in one octave band predominates. The weighted level of a spectrum that just touched the 150-minute curve in one octave band would be 10 m/s^2, and one that just reached the 400-minute curve would be 1 m/s^2. These latter figures could possibly be used as guidelines, with suitable interpolation, for intermediate exposures if a simple screening procedure is required.

Weighted measure, m/s^2	Latent interval, years
70	0.6
70	16.5
50	1.8
25	3.0
20	14.0
12	4.5
3	13.7

This weighted measure has been applied to some vibration spectra, including those discussed in this paper. The average latent period for a number of exposed populations is shown, together with the appropriate weighted level.

All the weighted levels exceed the value of 1 m/s^2 and, in general, appear to correlate well with the latent period. The 16.5-year latent period is associated with the use of the pneumatic paint remover, where the additional complication of the broken work pattern has already been discussed. The 14-year latent period is also unusual in that it occurred in a factory where pedestal grinding on a softer type of grinding wheel was in operation. Also, and perhaps more significantly, the work pattern was much more varied and apparently less intensive than in other factories where the average latent period was less than 2 years.

CONCLUSION

Most of the spectra that have been quoted in this paper have been determined from only a few sample measurements of the work process, and their statistical reliability has not yet been investigated thoroughly. Therefore, although it appears progress towards the establishment of a damage risk criteria is being made, the conclusions drawn in this paper must remain tentative.

Points that require further consideration are:

1. Standardization of measurement and presentation of vibration data, including a study of the time duration of a signal, are needed to obtain a statistically reliable spectrum. Where the nature of the work process means that this duration cannot be achieved, it will be necessary to measure a sufficient number of samples to obtain a reliable ensemble average.
2. To evaluate the exposure, medical and epidemiological field studies must be continued to quantify the dose-response relationship. As has already been suggested, the evaluation of exposure using dosimeter techniques is too limited and their use will cause too much information on the time history of the exposure to be lost. At the same time, as these studies are pursued, investigations of the dynamic characteristics of the hand-arm system must be continued. A knowledge of the mechanical impedance of the hand-arm system will help identify the relative importance of different frequencies, but it will not clarify the dose-response relationship. Clearly, measurement of vibration on hand-held equipment still has an important role to play.
3. To effectively collate vibration data with the medical and epidemiological data, there must be cooperation among research establishments, manufacturers, and users. Constructive comments on existing proposals should be welcomed, and international discussion should continue so that in the fullness of time a definitively universally accepted standard will emerge.

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QUESTIONS AND ANSWERS

Question (F. Dukes-Dobos, NIOSH): I would like to ask what underlying criteria did you apply when you determined the U.K. standard? Is this based on average data or a certain percentage of the observed population? The question then becomes what percentile of an exposed population would be safe if the proposed limits were observed?

Answer: The first point is that the U.K. draft standard is based on the same basic data as was the ISO proposal; in other words, subjective data of what vibration levels are acceptable, intolerable, unpleasant, etc. They are not based on any epidemiological data. The percentile information is therefore not discussed in the proposals.

Question (F. Dukes-Dobos): For the purposes of your standard, where do you measure the vibration magnitude?

Answer: On the workpiece itself.

Question (H. Gage, New Jersey Institute of Technology): Now, following up on the last question, how did you make measurements? On the tools themselves? What did you do? Mold accelerometers on the body of the tool? How did you do that?

Answer: In the case of the grinding processes, the accelerometer was screwed rigidly into the casting that was being handled. With the chainsaw, they were mounted by means of Jubilee* clips onto the handle in most instances. Occasionally, where circumstances allowed, we screwed the accelerometer directly into the handle; and on pneumatic tools, again, we usually used Jubilee clips, although on occasions, we fitted the accelerometer directly into the workpiece itself. Some work we've done suggests that the use of the Jubilee clip introduces resonances associated with the mounting of the clip, which might produce slight changes in the spectrum.

*Hose clip.

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