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FOUNDATIONS OF HAND-TRANSMITTED VIBRATION STANDARDS

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ABSTRACT

Standards for hand-transmitted vibration predict dependent variables (e.g. finger blanching) from measurements of a few independent variables (e.g. vibration magnitude, vibration frequency, exposure duration). This paper illustrates the assumptions in the current International Standard guidelines for the evaluation of hand-transmitted vibration and compares research methods which may provide information to improve the guidance. Subjective assessments of vibration discomfort have influenced the frequency weighting used in current standards, but the data have been modified greatly for this purpose. Subjective and biodynamic data suggest that the severity of vibration may not be similar for vibration occurring in different axes. Physiological and pathological studies seek to uncover the mechanisms involved in the temporary and permanent changes caused by vibration, but they have yet to contribute to the guidance in standards. Future experimental studies in humans are unlikely to be sufficient to determine how injury depends on the characteristics of vibration exposures at work. Epidemiological studies are required to uncover the effects of occupational exposures, but the complexity of occupational exposures will prevent the formulation of standards based solely on the results of epidemiological studies. Standards for hand-transmitted vibration include unproven assumptions but, for those assessing the severity of occupational exposures, they offer the most reasonable method for predicting the likely effects of vibration. A combination of subjective, biodynamic, physiological, pathological and epidemiological studies is required to improve current guidance.

Key Words: Vibration, Standards, Injury, Disease, Hand

INTRODUCTION

A foundation is a support upon which to build. The function, significance and beauty of a construction are at the mercy of its foundations. A standard for hand-transmitted vibration will not endure the tests of time if its foundations are not secure. As builders may aspire to dazzle their contemporaries or endow future generations, so standards may be supported on the quick sands of current opinion or upon the repeatable observations of scientists.

Standards encourage uniformity so as to assist communication and the comparison of information. This paper seeks to identify the foundations required for hand-transmitted vibration standards to achieve this objective.

Identifying the problem

A standard for the measurement and evaluation of hand-transmitted vibration must define how to quantify the relevant independent variables (vibration magnitude, vibration frequency, exposure duration, etc.). The measurement and evaluation of the relevant dependent variables (e.g. finger blanching) might also be standardised. A standardised dose-effect relationship could

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then define a method of predicting the dependent variables from measurements of the independent variables.

In the fields of acoustics and vibration it is common to use a 'frequency weighting' to allow for the differing sensitivity of the body to different frequencies of oscillation. An exposure to any frequency of vibration may then be expressed in terms of the magnitude at a chosen frequency which is thought to produce an equivalent effect. The concept can be extended to also define a weighting for the duration of exposure so that any exposure duration can be expressed in terms of the magnitude of vibration required at a chosen duration which is thought to produce an equivalent effect.

If weightings can be specified for all of the variables which contribute to the effect (i.e. all independent variables), the dose-effect relationship can be expressed mathematically (see Table 1). Such formulations assume that the effect of each variable is known, that the effect is a continuous function, and that there are no interactions between variables. The equations in Table 1 also assume that each independent variable can be represented by only one value. It is unlikely that these assumptions are valid, but the formulation shown in Table 1 will be sufficient for the present purposes.

Table 1. Concept of 'weighted acceleration'.

$$\text{prevalence of finger blanching} = K.\ (\text{weighted acceleration})^n$$

$$\text{weighted acceleration} = a \times H_f \times H_m \times H_y \times H_a \times H_f \times H_p \times H_e \times H_i$$

where:

a = magnitude of the acceleration;

H_f = weighting for frequency of vibration;

H_m = weighting for minutes exposure per day;

H_y = weighting for years of exposure;

H_a = weighting for axis of vibration;

H_f = weighting for force of grip and push;

H_p = weighting for posture of fingers, hands and arm;

H_e = weighting to allow for environmental conditions;

H_i = weighting to allow for individual susceptibility.

In ISO 5349 (1986):

$$\text{prevalence of finger blanching} = K.\ (\text{weighted acceleration})^2$$

and,

$$\text{weighted acceleration} = a \times H_f \times H_m \times H_y,$$

where:

$K = 0.0111$

a = r.m.s. acceleration (ms^{-2})

H_f = frequency weighting (i.e. W_h)

$H_m = (t/T_{(4)})^{½}$, where the daily exposure duration, t, and reference duration $T_{(4)}$ are in the same units;

H_y = years of regular daily vibration exposure.

Ways of building the foundations

The relative importance of different independent variables might be discovered by the study of subjective responses, biodynamic responses, or physiological and pathological responses to vibration. The studies may involve experimental exposures to vibration in the laboratory or the examination of the hands of those exposed to vibration in their occupations (i.e. epidemiological studies).

Objective of paper

The identification of variables shown in Table 1 is used to consider the state of knowledge supporting the development of standards for evaluating hand-transmitted vibration and predicting its effects. After illustrating the form of the current International Standard, the methods which are being used to discover the effects of hand-transmitted vibration are reviewed.

INTERNATIONAL STANDARD 5349 (1986)

International Standard 5349 (1986)[1)] provides a frequency weighting, called Wh in the equivalent British Standard[2)] (i.e. BS 6842, 1987). International Standard 5349 (1986) expresses the daily exposure in terms of the 'energy-equivalent' frequency-weighted acceleration for a period of 4 hours. This 'energy-equivalence' defines the time-dependency of human response to vibration of differing daily exposure durations. Annex A to ISO 5349 (1986) implies a different weighting for years of exposure. The weightings for vibration frequency, daily exposure duration and years of exposure as implied in ISO 5349 (1986) are illustrated in Fig. 1 with linear scales on the abscissae and ordinates.

In International Standard 5349 (1986),[1)] all directions of vibration are considered to be of equal importance, and so there is no 'axis weighting'. Only the directional component with the largest weighted acceleration is used in the assessment of the exposure.

In International Standard 5349 (1986) there is no weighting for grip force, push force,

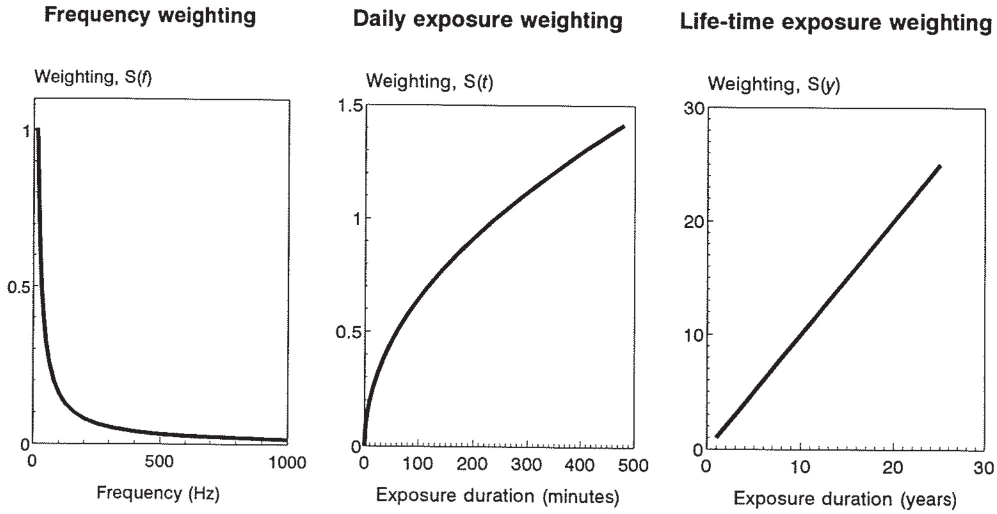

Fig. 1. Weightings for vibration frequency, exposure time during the day and years of exposure as implied by ISO 5349 (1986).[1)] All three figures on linear scales.

posture or intermittency in vibration exposure, or any other variable. The severity of the vibration exposure is therefore solely dependent on the magnitude and frequency of vibration and the daily and yearly exposure durations.

Annex A to ISO 5349 (1986) defines a procedure for predicting the duration of vibration exposure necessary before the onset of vascular symptoms (i.e. finger blanching). A formula is given which can be used to evolve other expressions (as in Table 2) and determine the implied weightings for both minutes of exposure per day and years of exposure (see Table 1).

Fig. 2 shows how the years of exposure required for 10% to 50% of persons to develop finger blanching depend on the 4-hour energy-equivalent acceleration. Fig. 2 is presented with linear axes: the same data are presented with logarithmic axes in the standard. Fig. 3 shows how the incidence of finger blanching is assumed to depend on the 4-hour energy-equivalent acceleration for exposure durations from 1 to 25 years. Fig. 4 shows how the incidence of finger blanching depends on the frequency-weighted acceleration for daily exposure durations from 10 minutes to 480 minutes if the exposure lasts for 8 years. In both cases, the incidence of finger blanching increases in proportion to the square of the acceleration. Consequently, with low magnitudes of vibration there appears to be little problem unless there is a long duration of exposure, while with high magnitudes of vibration, finger blanching is predicted unless the exposure duration is brief.

Fig. 5 shows how the years of exposure required for 10% of exposed persons to develop finger blanching depend on the vibration magnitude, for daily exposure durations between 10 minutes and 8 hours. As presented in ISO 5349 (1986), the years of exposure shown in Fig. 4 are not the average of the latent periods before the development of finger blanching among the first 10% of the exposed population to develop banching. The values are said to be the 'years of regular vibration exposure before episodes of finger blanching occur in 10% of exposed persons'.

Table 2. Dose-effect formulae derived from ISO 5349.

In terms of frequency-weighted acceleration a_w:

$$a_{hw} = \frac{9.5}{E}\left[\frac{C.T_{(4)}}{t}\right]^{1/2} \qquad E = \frac{9.5}{a_{hw}}\left[\frac{C.T_{(4)}}{t}\right]^{1/2} \qquad C = \left[\frac{a_{hw}.E}{9.5}\right]^{2}.\frac{t}{T_{(4)}} \qquad t = C.T_{(4)}\left[\frac{9.5}{a_{hw}.E}\right]^{2}$$

In terms of the 4 hour 'energy-equivalent' frequency-weighted acceleration, $a_{hw(eq,4h)}$:

$$a_{hw(eq,4h)} = \frac{9.5}{E}.\sqrt{C} \qquad E = \frac{9.5}{a_{hw(eq,4h)}}.\sqrt{C} \qquad C = 100.\left[\frac{a_{hw(eq,4h)}.E}{95}\right]^{2}$$

where:

a_{hw}	=	frequency-weighted acceleration (ms^{-2} r.m.s.)
E	=	years of regular exposure to vibration;
C	=	prevalence of VWF (expressed as a percentage);
$T_{(4)}$	=	4 hours (in same units as t);
t	=	daily exposure duration.
$a_{hw(eq,4h)}$	=	4-hour energy-equivalent frequency-weighted acceleration

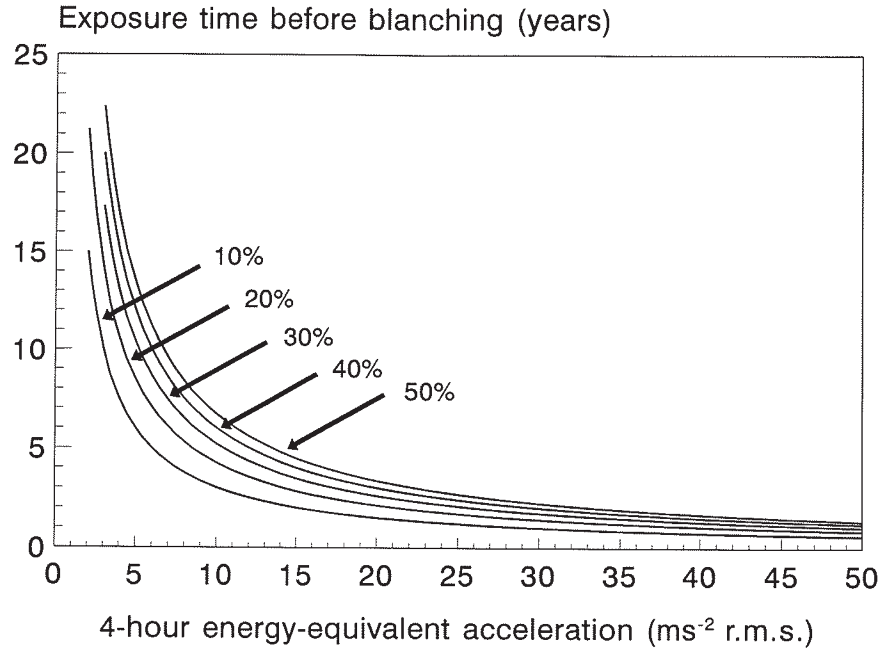

Fig. 2. Exposure time before finger blanching for different percentiles (10% to 50%) of a population group exposed to hand-transmitted vibration. Figure presented on linear scales.

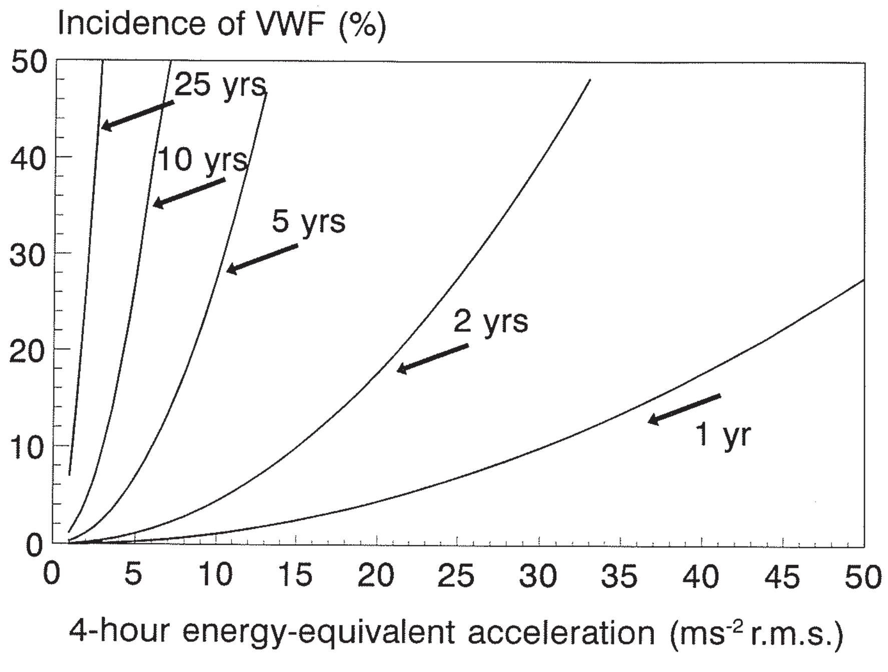

Fig. 3. Incidence of finger blanching as a function of vibration magnitude for lifetime exposures from 1 to 25 years. Acceleration assumes 4 hour exposures per day (i.e. $a_{hw(eq,4h)}$)

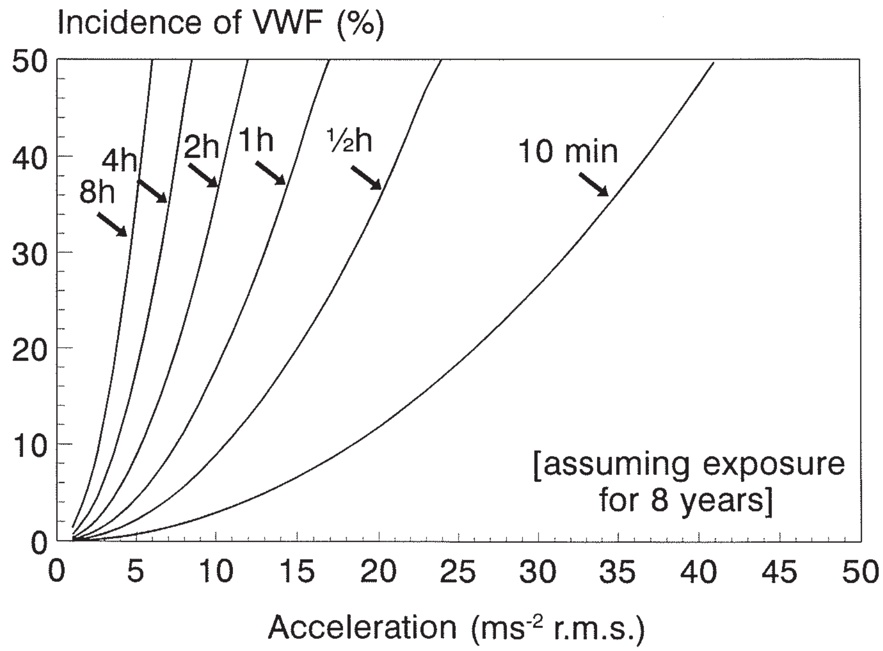

Fig. 4. Incidence of finger blanching after 8 years as a function of vibration magnitude for daily exposure durations from 10 minutes to 8 hours.

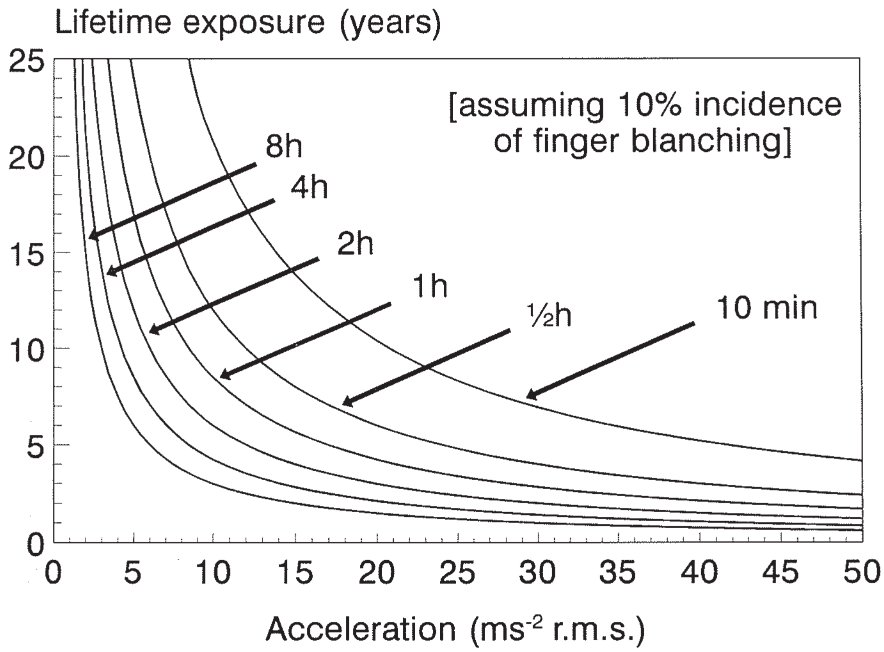

Fig. 5 Lifetime exposure required for 10% incidence of finger blanching as a function of vibration magnitude for daily exposures from 10 minutes to 8 hours.

Fig. 6 shows how the 4-hour energy-equivalent magnitude of vibration required to produce finger blanching in 10% of persons depends on the frequency of vibration for exposure periods between 1 and 25 years. Fig. 7 shows how the r.m.s. magnitude of vibration required to produce finger blanching in 10% of exposed persons after 8 years of exposure depends on the frequency of vibration for daily exposure durations from 1 minute to 8 hours.

The equations in Table 2 define the form of the relationships illustrated in Fig. 1 to 7. These figures summarise the implications of International Standard 5349 (1986) and many equivalent National Standards. Some older standards and some newer proposals differ from the above guidance. Nevertheless, any standard which allows the prediction of the occurrence of vibration-induced white finger from the measurement of vibration requires these, or alternative relationships. The following sections summarise the foundations on which ISO 5349 (1986) was constructed.

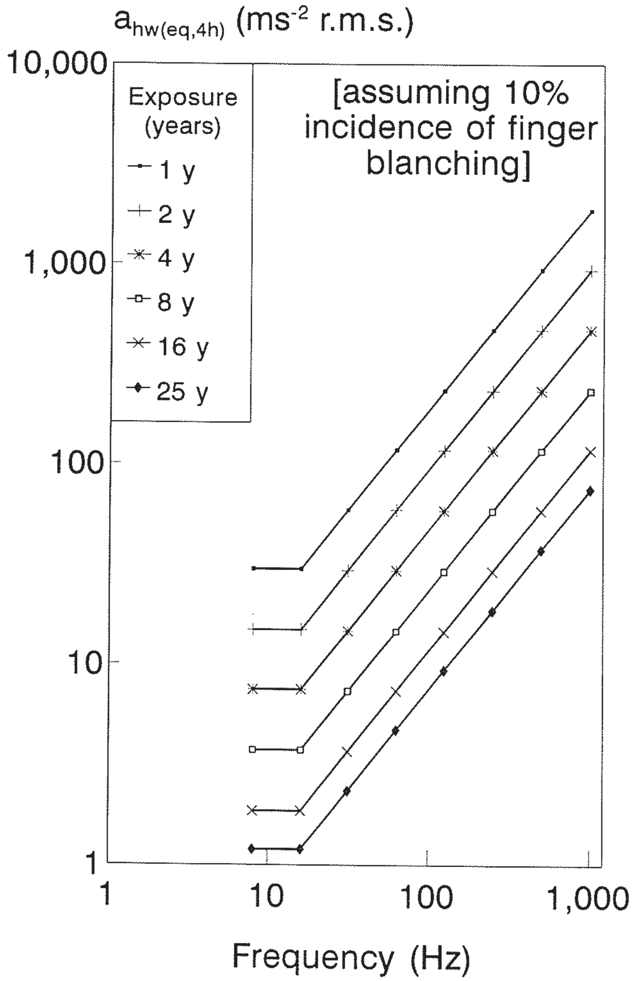

Fig. 6 Vibration magnitude required to produce 10% incidence of finger blanching for exposure periods from 1 year to 25 years as a function of vibration frequency. Assumes 4 hour exposures per day (i.e. acceleration magnitude is $a_{hw(eq,4h)}$)

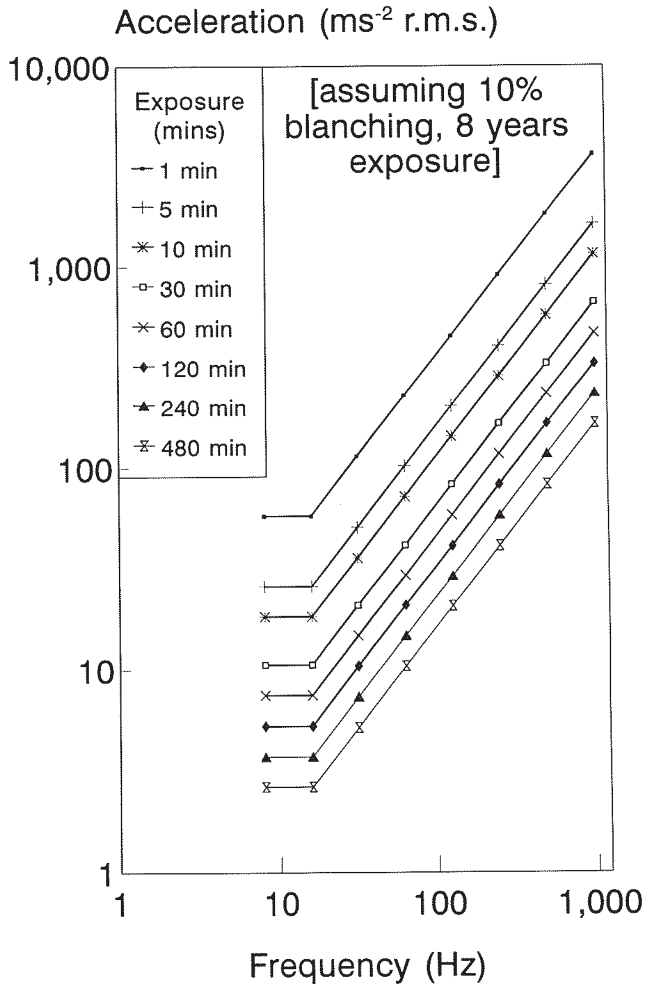

Fig. 7. Vibration magnitude required to produce 10% incidence of finger blanching after 8 years as a function of vibration frequency for daily exposure durations from 1 minute to 8 hours.

SUBJECTIVE FOUNDATIONS

Studies of the effects of the frequency of vibration show that higher magnitudes of acceleration are required to cause discomfort at higher frequencies of vibration.[3–5] see Fig. 8. There are insufficient data to suggest that there is a consensus of opinion as to how discomfort changes with frequency. This is partly because rather few investigations have been performed and partly because discomfort also depends on other variables (e.g. force of contact and hand posture).

Fig. 8 shows that the discomfort caused by the vibration of a handle can depend on the axis of vibration in addition to the frequency of vibration. For the data shown there is as much as about 5:1 difference between axes at some frequencies. It is likely that the relative sensitivity between axes will depend on the grip force, the orientation of the hand and the posture of the arm. Fig. 8 strongly suggests that it may not be appropriate to assume that all three axes of vibration are equally severe, as implied in ISO 5349 (1986).

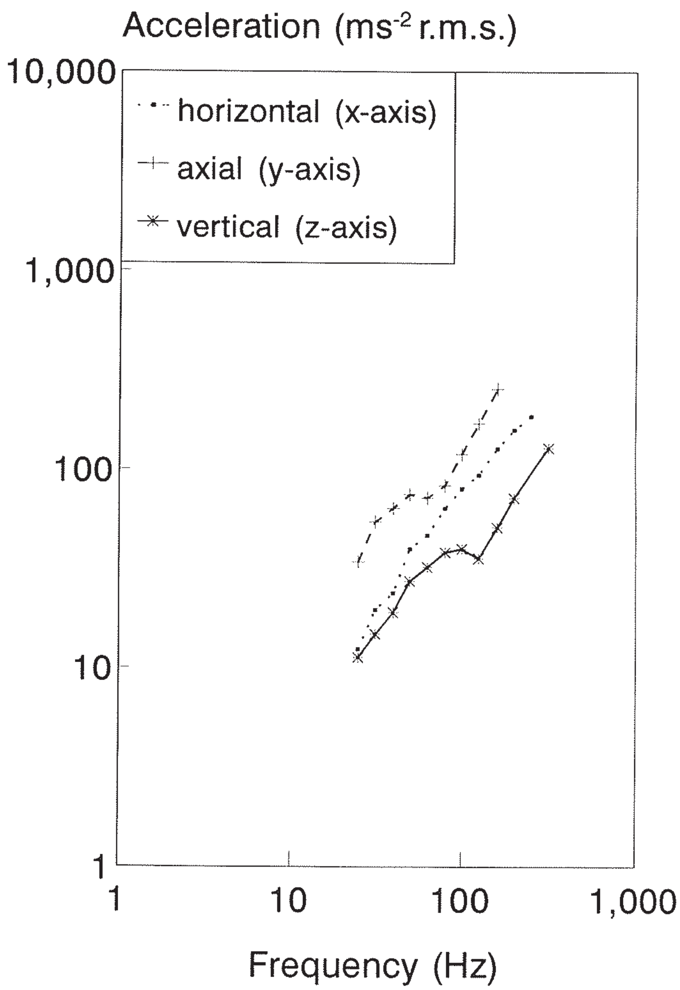

Fig. 8. Equivalent comfort contours for vibration transmitted from a horizontal handle; contours correspond to 'would not want to clasp the handle for an extended period of time'. Adapted from Reynolds et al.[5)]

The subjective data obtained by Miwa[3,4)] have been very influential in the evolution of standards for the evaluation of hand-transmitted vibration. With 10 subjects, he determined 'equal sensation' contours for vertical and horizontal vibration of the hand pressed on a flat horizontal surface. He investigated the frequency range 3 to 300 Hz and concluded that there was no difference in the response to the two directions of vibration. In the range 6 to 60 Hz Miwa found that his mean contour could be approximated by a line of constant velocity, below 6 Hz he suggested a line of constant acceleration and above 60 Hz a line of constant displacement (see Fig. 9). The Japanese Association of Industrial Health[6)] 'adjusted' this contour to constant acceleration from 2 to 16 Hz and constant velocity from 16 Hz to 300 Hz. This changed the weighting at 300 Hz by a factor of 5 from that proposed by Miwa. International Standard 5349 (1986) employs the weighting proposed by the Japanese Association of Industrial Health with constant acceleration from 8 to 16 Hz and the range of constant velocity above 16 Hz extrapolated to 1000 Hz. This produces a limit at 1000 Hz which is a factor of 16 lower than it would have

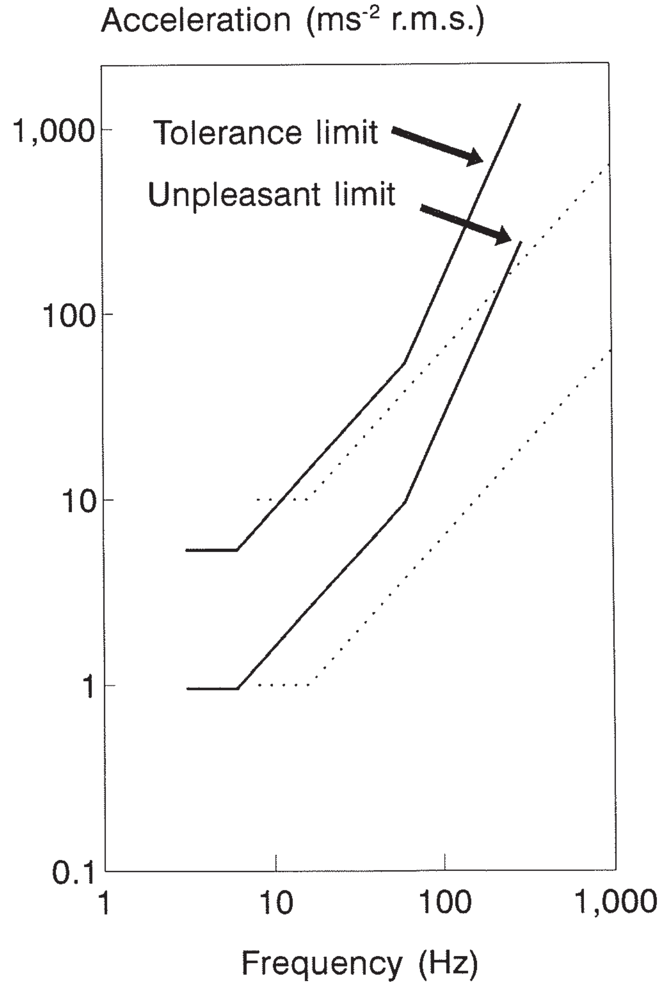

Fig. 9. The 'tolerance limit' and 'unpleasant limit' determined by Miwa[4] compared with contours having the same frequency-dependence as ISO 5349 (1986).

been if the extrapolation was based on Miwa's constant displacement approximation to his data! Although the work of Miwa provided the starting point for the frequency weighting in ISO 5349 (1986) it cannot be said to have defined the frequency dependence used in the standard: the weighting in ISO 5349 (1986) is influenced by convenience and undocumented compromise within committees.

Subjective data had some influence on the vibration 'limits' proposed in early standards. In the absence of other information, it might seem reasonable that an injury limit should take into account sensations, such as 'unpleasantness'. However, this leads to limits with an undefined meaning (e.g. in Draft International Standard 5349 (1979)[7] the number of persons protected by proposed limits was not stated). Dose-effect information is required to formulate satisfactory limits: the extent of discomfort caused by vibration is not the relevant dependent variable when formulating dose-effect relationships for vibration-induced injuries.

Perception thresholds might contribute to the provision of guidance on the effects of hand-transmitted vibration. However, the tactile perception of vibration is highly dependent on the geometry of the contact with the source of vibration: this affects the sensitivity of the different end-organs and the manner in which thresholds for vibrotactile perception depend on vibration frequency. There is insufficient evidence to conclude that the simple reflection of any one vibrotactile sensitivity contour would be appropriate for defining the manner in which injury depends on vibration frequency. However, perception threshold data may be particularly useful when considering the neurological effects of hand-transmitted vibration. For example, studies show that the method of evaluation proposed in ISO 5349 (1986) does not provide a good prediction of the temporary threshold shifts produced by time-varying exposures to hand-transmitted vibration.[8]

BIODYNAMIC FOUNDATIONS

Studies of the mechanical impedance[9–11] and the transmissibility[12–14] of the fingers and hand show that at low frequencies the hand and arm are closely coupled but that, as the frequency

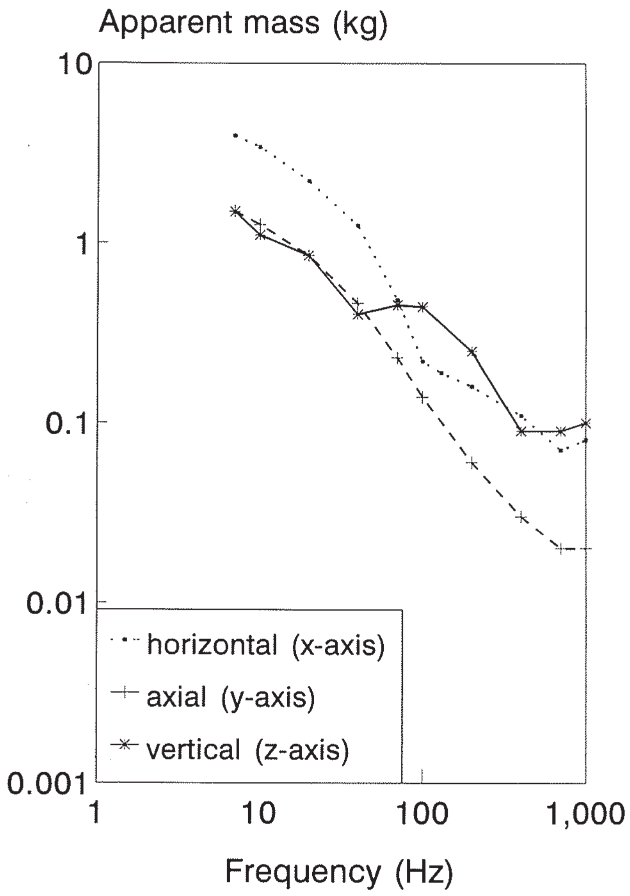

Fig. 10 Apparent mass of the hand in three axes for a horizontal hand and forearm and a palm grip around a horizontal handle. Adapted from Reynolds et al.[9]

increases, the affected part is increasingly located nearer to the source of excitation. Again, the manner in which the response depends on frequency is affected by the axis of vibration and the grip and push force in addition to the posture of the arm. There are attempts to produce a standardised model of the biodynamic response of the hand-arm system. However, the effects of major variables contributing to this response are inadequately identified for such a model to be generally useful for the prediction of injury. The data shown in Fig. 10 indicate that there can be a large difference in mechanical impedance between axes. This may be expected to correspond to a differing energy absorption in each axis and is not consistent with the use of the same frequency weighting for all axes, as in current standards.

PHYSIOLOGICAL AND PATHOLOGICAL FOUNDATIONS

It might seem that physiological and pathological studies would provide the best foundation for hand-transmitted vibration standards. However, this presupposes that the mechanisms of damage are known and that useful studies are ethical and safe. Current standards for evaluating hand-transmitted vibration have not been influenced by experiments in which physiological or pathological mechanisms have been investigated.

A major role for this type of study would appear to be the uncovering of the mechanisms involved in the temporary and permanent changes caused by hand-transmitted vibration. This presents a significant challenge in view of the complex physiology and the varied signs and symptoms associated with hand-transmitted vibration. Although models of the mechanisms of injury exist, they are primarily the subject of scientific study rather than the support for new standardisation.

When the relevant physiological and pathological changes and have been uncovered it will remain to determine how they are related to the physical conditions which caused them. It is not certain that experimental studies with humans could be used to determine how the changes depend on the frequency, direction, duration, grip force, temperature etc. of vibration exposures. Even if ethical, such studies would take a great deal of time. It seems likely that the effects of some of these variables will be suggested by other means (e.g. biodynamic studies) and the results used to predict the physiological or pathological effects. So, for example, biodynamic and subjective data may contribute to a model which predicts the relative effects of different physical variables and the predictions may be tested by physiological or pathological studies. By this means, the value of the physiological and pathological studies may be extended to a wider range of conditions.

EPIDEMIOLOGICAL FOUNDATIONS

Laboratory studies do not come close to replicating the conditions which cause vibration injury in occupations: it can be difficult to reproduce both the complex and constantly varying vibration conditions and the complex and variable contact with the source of vibration. It is impractical to reproduce a full day's exposure to vibration in the laboratory and impossible to reproduce the years of exposure often necessary to cause the injury or disease.

Laboratory studies have the advantage that they can control the causal conditions so as to allow more precise study of cause-effect relationships. However, they have a major disadvantage in that they cannot produce the effect (i.e. the disorder) which is of greatest interest. Epidemiological studies have the advantage of being able to study the disorder but the disadvantage of being unable to control the causal conditions. The two types of study are complementary.

Many epidemiological studies of the effects of hand-transmitted vibration have been reported.[15] The relevant research includes simple summaries of symptoms claimed by exposed persons and both cross-sectional and longitudinal studies in which clinical examinations or scientific tests have been conducted.

There is both agreement and disagreement among the findings of epidemiological studies. It is clear that hand-transmitted vibration from many sources can cause a range of disorders. It is not clear which exposure conditions cause each type of disorder.

Epidemiological studies cannot be expected to provide all the information necessary to establish standards for the evaluation of hand-transmitted vibration. Even the evolution of a frequency-weighting is impossible using epidemiological data alone. In the laboratory, each frequency can be studied separately and the magnitude required to produce an effect can be determined. In the field, tools produce complex vibration spectra and the hand is exposed to motion in all three axes. Suppose two tools (A and B) are evaluated by the frequency weighting in ISO 5349 (1986) and tool A is associated with a higher incidence of a disorder than would be expected by this standard. The difference might be attributed to the presence of, say, more high frequency vibration on tool A. This is only one of several possible hypotheses: the additional high frequency vibration can only be accepted as the explanation if all other causal variables (exposure duration, grip, etc.) are the same for both tools, but this is most unlikely. Only when several other studies with different conditions yield similar hypotheses as to the importance of high frequency vibration, and this becomes the only reasonable explanation for all findings, can the hypothesis become a belief. Even then, the data are not sufficient to define how the frequency weighting should be changed: at most, the data will suggest a change in the relative importance of vibration at two frequencies.

It might be thought that by studying the incidence of a disorder in large numbers of persons using a variety of tools a statistical procedure could be used to evolve the frequency weighting which best predicts the observed effects. In practice, it is not possible to measure the true vibration exposure of all persons over their full duration of exposure: substantial assumptions have to be made as to the vibration spectra to which each person has been exposed. It will also be found that tools which have a high magnitude of vibration at one frequency also tend to have high magnitudes at other frequencies and in other directions.[16] In consequence, statistical procedures applied to epidemiological data are unlikely to establish the full form of the appropriate frequency weighting.

Few recent epidemiological studies have been conducted to evolve methods of evaluating hand-transmitted vibration: studies have mostly tested the predictions of the currently recommended evaluation procedures. Several studies have suggested that the prediction procedure in ISO 5349 (1986) overestimates or understimates the prevalence of finger blanching.[17–19] At least one study has found that the correlations between vibration magnitudes and the extent of vibration-induced white finger is not increased by the use of the frequency weighting in ISO 5349.[20]

The data from epidemiological studies were used to evolve the dose-effect relationships in the current International Standard but they had little influence on the vibration evaluation procedure.

A detailed analysis of latency data has been reported by Brammer.[21,22] Using the Taylor-Pelmear system of staging VWF, he concluded that the interval before stage 3 symptoms develop is 3.2 times the latent interval and that the distribution of latent intervals in a group is normally distributed with a standard deviation proportional to 0.46 times the average latent interval of the group. (In this context the latent interval is the period of employment before the initial appearance of a white fingertip.) Both of these relations are reported to be independent of the vibration magnitude. Brammer then proposed various 'rules' on which only some of the published data should be used to formulate dose-effect data — these primarily exclude data from small groups and restrict considerations to groups with a prevalence greater than 50%. Using the same frequency-weighting as in International Standard 5349 (1986) and the results from seven studies having weighted accelerations between about 12 and 28 m/s^2 r.m.s. and latencies between 2 and 5.7 years, he concluded that the average latent interval, L_t is given by:

$$L_t = 78.7/a_{hw}$$

Assuming a normal distribution and the above relation between stage 3 symptoms and latency, various predictions can be made of the percentage of persons affected. This method of analysis does not necessarily give accurate predictions for the many cases where the weighted vibration magnitudes are below 10 m/s^2 r.m.s., the average latency is long or the prevalence is below 50%. Although the use of the ISO 5349 (1986) frequency weighting yielded a high correlation between average latent interval and weighted acceleration, it cannot be concluded that these data substantiate its form: there was probably little high frequency or low frequency energy on the tools concerned.

Considering the problem of predicting the effects when the prevalence is low, Brammer argued that in a group having any given prevalence, P, the average latent interval will be the duration of exposure when the prevalence was 0.5 P. He suggests that the concept of normal distribution mentioned above can be used to find the exposure duration corresponding to any selected prevalence. The weighted acceleration corresponding to this latent interval was then obtained from the above equation.

Brammer illustrates his relation between prevalence and latent interval using unpublished information from a study of a group of chain sawyers having a mean latency of about 3 years. The relation between latency and prevalence predicted from measurements of tool vibration is in apparent agreement with values obtained in the study. A second example uses data obtained from a group of 54 men working with hand-held grinders having a weighted acceleration of 3 m/s^2 r.m.s. The group had 20 men (37%) with symptoms of blanching and a reported mean latent interval of 13.7 years. He shows that, as expected, the mean latent interval is lower than would be predicted from the measured vibration using the relation between vibration magnitude and acceleration determined with groups having somewhat higher prevalence rates. Brammer points out that the prediction required considerable extrapolation of the previous data and concludes that such extrapolation is justified by the agreement obtained in this case. He then used the method to construct a table showing the predicted latencies (from 2 to 35 years) as a function of weighted acceleration (from 1 to 25 m/s^2 r.m.s.) and prevalence (from 10 to 50%). He illustrated latencies for a 5% prevalence at about one-quarter the weighted acceleration required to produce 50% prevalence. The values assume that the basic relation between latency and vibration magnitude applies to a prevalence of 50% and that the method can be further extrapolated to prevalence rates below 37%. The data used for this analysis were thought to be from tools for which vibration entered the hands throughout the day so do not apply if vibration exposure occurs for a shorter period. If the numbers of persons entering or leaving a vibration-exposed group differ from those for the groups upon which the formulae are based there will be additional discrepancies. (From an analysis of Japanese data, Futatsuka et al.[23] also found that the prevalence increased with duration of vibration exposure but, for the same vibration conditions, their prevalence rates were lower: 4, 8 and 15% corresponding to 10, 20 and 40% suggested by Brammer.)

From the above relations, Brammer suggests a threshold weighted acceleration for the production of vibration-induced white finger in the range 1.0 m/s^2 r.m.s. (10% prevalence after 30 years) to 2.9. m/s^2 r.m.s. (50% prevalence after 25 years). As a threshold for the occurrence of vascular symptoms, this range is roughly consistent with data from other studies[23–25] and earlier vibration standards. Brammer has subsequently investigated the applicability of his various dose-effect relationships which were used to formulate the 1986 version of Annex A to ISO 5349.[26,27]

Individual studies will sometimes find significant differences between the predictions from any standard and the occurrence of blanching in the exposed population. A cause for this difference may then be hypothesised. This must be recognised as an hypothesis, to be tested in a wider range of conditions, rather than a sufficient basis to difine a new evaluation procedure. When it is deemed appropriate to propose a revised evaluation procedure it is necessary to consider the wider implications of the change. A proposal for revising a standardised evaluation procedure should contain:

(i) a precise definition of the proposed change;
(ii) evidence supporting the change;
(iii) a consideration of the effects of the change on previously reported data;
(iv) an estimate of the improvement in accuracy of predictions arising from the adoption of the proposed change.

For example, it is easy to suggest that the frequency range of current standards should be extended to frequencies above 1000 Hz. However, this requires the definition of the appropriate frequency weighting for the higher frequencies. In many cases, an extrapolation of the current frequency weighting (or weightings implied by equivalent comfort contours) would attenuate the high frequencies such that they would contribute very little to the measurements, yet the required signal-to-noise ratio of instrumentation and the rigidity of the coupling of accelerometers to tools would be severely tested.

It may be concluded that epidemiological data alone will not be sufficient to evolve the vibration evaluation procedures required for hand-transmitted vibration standards. Epidemiological data may make an essential contribution to the procedures and epidemiological studies are required to test the predictions of alternative vibration evaluation procedures.

DISCUSSION AND CONCLUSIONS

Hand-transmitted vibration standards may define the measurement of 'dose', the measurement of the 'effect', or a 'dose-effect' relationship. In each case it is necessary to consider several variables and, with current understanding, make assumptions as to its importance. Users of standards should be informed as to the basis of the assumptions.

The different methods of studying the effects of hand-transmitted vibration yield complimentary data. No single method will yield all the desired information. Table 3 suggests how understanding of the effects of vibration on the various dependent variables has influenced the current International Standard for evaluating hand-transmitted vibration. It is suggested that practical 'convenience' has contributed as much as knowledge of the subjective, biodynamic, physiological, pathological and epidemiological responses to vibration.

Subjective and biodynamic responses to vibration will influence future standards. Laboratory investigations will define how the transmission of vibration to the hand and the sensations it produces depend on the characteristics of the vibration (frequency, direction, magnitude, etc.), and how they vary with the characteristics of the contact with vibration (handle size, shape and orientation etc.), the posture of the body and other aspects of the individual.

Physiological and pathological experimental studies may contribute to understanding the mechanisms of the changes caused by vibration and investigate how they depend on some of the

Table 3. Relationships between dependent and independent variable influencing the form of International Standard 5349 (1986).[1] (The dependent variables represent areas of study and may, in some cases, involve the measurement of the same variable).

VARIABLES	INDEPENDENT VARIABLES (i.e. dose)							
DEPENDENT VARIABLES (i.e. effect)	frequency	axis	duration		grip	Environmental conditions	Dose-effect	
			hours	years			susceptibility	Magnitude
comfort	*	-	-	-	-	-	-	-
biodynamics	-	-	-	-	-	-	-	-
physiology, pathology	-	-	-	-	-	-	-	-
epidemiology	-	-	-	*	-	-	*	*
convenience	*	*	*	*	-	-	*	*

* contributed to form of current standard

characteristics of the vibration and other variables.

Epidemiological studies will help to uncover the effects of some independent variables (especially exposure duration) and contribute to the testing of proposed dose-effect relationships.

The writers of standards containing dose-effect guidance should consider the accuracy that will be obtained when making predictions using the recommended guidance. The expected accuracy should be specified in the standard, or it should be stated that the accuracy cannot be specified. With current standards the accuracy cannot be specified. This is not solely a consequence of inadequate information on the relationship between the frequency-weighted energy-equivalent acceleration and the occurrence of finger blanching. It is primarily a consequence of insufficient understanding of the effects of the independent variables (vibration frequency, direction and duration, contact force, etc.) which are assumed within the evaluation procedure.

Standards for hand-transmitted vibration can be useful even if they have an unknown accuracy. The unification of measurement and evaluation techniques can help to communicate information about vibration magnitudes. The categorisation of the effects of vibration may increase awareness of the hazards of vibration. Even imperfect dose-effect guidance indicates that the hazards may be lessened by reductions in vibration magnitude or reductions in exposure duration. It is possible that current dose-effect guidance may suggest reductions in vibration severity where this is not necessary — but health monitoring will often be used to establish whether a problem really exists. It is possible that current dose-effect guidance may have suggested that some vibration exposures are less severe than is really the case — but the guidance is unlikely to imply zero risk and an under-estimated risk should be detected when problems appear. This is similar to the situation with no dose-effect guidance — except that the existence of the guidance has increased awareness of the possible outcome and increased the ability to predict the outcome.

The accuracy of the dose-effect information in current and future standards could be greatly improved if it were restricted to the conditions (e.g. tool types) from which it was obtained. The interpolation and extrapolation of data so that the measurement and evaluation methods can be applied to all types of vibration is a major source of uncertainty. By restricting guidance to specific tool types it may be possible to specify its accuracy: the uncertainty surrounding the effects of vibration frequency and other variables then become less important because similar tool types have similar vibration spectra, grip forces, etc. The user of a standard might tentatively use dose-effect guidance derived from chain saws to predict the effect of chipping hammer vibration, but the assumption being made will then be apparent to the user. At present, the interpolation and extrapolation made by the authors of standards are not known to those who apply their recommendations.

Incorrect guidance in hand-transmitted vibration standards may give significant problems in the design or selection of tools. For example, if the frequency weighting is incorrect it may lead to replacing a vibratory tool with another having a lower frequency-weighted acceleration but carrying a higher risk of injury. The assumptions in the measurement and evaluation procedure should therefore be considered in standards concerned with the 'type testing' of tools and not merely in standards defining dose-effect relationships.

It is not appropriate to limit the discussion of standards to the accuracy of the guidance they contain. The omission of guidance can also be important. The absence of any differential effect for different axes of vibration, or an effect of contact force, contact location, posture, interruptions in exposure periods or temperature may have a large influence on the accuracy of dose-effect predictions. Current standards also fail to provide any indication of the likely severity of the disorder. Further, they are restricted to the prediction of finger blanching and do not predict neurological, articular or other effects of hand-transmitted vibration.

Standards for hand-transmitted vibration make many unproven assumptions, but they define the most reasonable current method for predicting the severity of vibration exposures. So, while scientists work to improve their foundations, others should make use of the guidance they currently contatin.

REFERENCES

1) International Organization for Standardization: Mechanical Vibration — Guidelines for the measurement and the assessment of human exposure to hand-transmitted vibration. International Standard ISO 5349 (1986).
2) British Standards Institution: Measurement and evaluation of human exposure to vibration transmitted to the hand. British Standards Institution BS 6842 (1987).
3) Miwa, T.: Evaluation methods for vibration effect, Part 3 Measurements of threshold and equal sensation contours on hand for vertical and horizontal sinusoidal vibrations. *Ind. Health,* 5, 213–220 (1967).
4) Miwa, T.: Evaluation methods for vibration effect, Part 4. Measurements of vibration greatness for whole body and hand in vertical and horizontal vibrations. *Ind. Health,* 6(1), 1–10 (1968).
5) Reynolds, D.D., Standlee, K.G. and Angevine, E.N.: Hand-arm vibration, Part III: Subjective response characteristics of individuals to hand-induced vibration. *J. Sound Vib.,* 51(2), 267–282 (1977).
6) Anon: Sub-committee on hazards from local vibration. *Jpn. J. Ind. Health,* 12, 198–203 (1970).
7) International Organization for Standardization: Principles for the measurement and the evaluation of human exposure to vibration transmitted to the hand. International Organization for Standardization/DIS 5349 (1979).
8) Maeda, S. and Griffin, M.J.: Temporary threshold shifts in fingertip vibratory sensation from hand-transmitted vibration and repetitive shock. *Br. J. Ind. Med.,* 50, 360–367 (1993).
9) Reynolds, D.D.: Hand-arm vibration: A review of 3 years' research. Proceedings of the international Occupational Hand-Arm Vibration Conference, National Institute for Occupational Safety and Health, Cincinnati, 1975, *DHEW (NIOSH) Publication No. 77– 70,* pp.99–128 (1977).
10) Griffin, M.J., Macfarlane, C.R. and Norman, C.D.: The transmission of vibration to the hand and the influence of gloves. In *Vibration Effects on the Hand and Arm in Industry,* edited by Brammer, A.J. and Taylor, W., pp.103–116 (1982), John Wiley & Sons., ISBN 0-471-88954-7.

11) Burström, L.: Measurements of the impedance of the hand and arm. *Int. Arch. Occup. Environ. Health,* 62(6), 431–439 (1990).
12) Pyykkö, I., Fäkkilä, M., Toivanen, J., Korhonen, O. and Hyvarinen, J.: Transmission of vibration in the hand-arm system with special reference to changes in compression force and acceleration. *Scand. J. Work Environ. Health,* 2, 87–95 (1976).
13) Reynolds, D.D. and Angevine, E.N.: Hand-arm vibration, Part II: Vibration transmission characteristics of the hand and arm. *J. Sound Vib.,* 51(2), 255–265 (1977).
14) Sakakibara, H., Kondo, T., Miyao, M., Yamada, S., Nakagawa, T., Kobayashi, F. and Ono, Y.: Transmission of hand-arm vibration to the head. *Scand. J. Work Environ. Health,* 12(4), 359–361 (1986).
15) Griffin, M.J.: Handbook of human vibration. ISBN: 0-12-303040-4 (1990), Academic Press, London.
16) Nelson, C.M. and Griffin, M.J.: Vibration-induced white finger in dockyard employees. Institute of Sound and Vibration Research, *Technical Report 170,* University of Southampton (1989).
17) Engström, K. and Dandanell, R.: Exposure conditions and Raynaud's phenomenon among riveters in the aircraft industry. *Scand. J. Work Environ. Health,* 12(4), 293–295 (1986).
18) Bovenzi, M., Franzinelli, A. and Strambi, F.: Prevalence of vibration-induced white finger and assessment of vibration exposure among travertine workers in Italy. *Int. Arch. Occup. Environ. Health,* 61, 25–34 (1988).
19) Starck, J., Pekkarinen, J. and Pyykkö, I.: Physical characteristics of vibration in relation to vibration-induced white finger. *Am. Ind. Hyg. Assoc. J.,* 51(4), 179–184 (1990).
20) Nelson, C.M. and Griffin, M.J.: Comparison of predictive models for vibration-induced white finger. In *Proceedings of the 6th International Conference on Hand-arm Vibration,* edited by Dupuis, H., Christ, E., Sandover, J., Taylor, W. and Okada, A., pp.875–883, (1993), HVBG, D-53754 Sankt Augustin, ISBN: 3-88383-331-2.
21) Brammer, A.J.: Relations between vibration exposure and the development of the vibration syndrome. In *Vibration Effects on the Hand and Arm in Industry,* edited by Brammer, A.J. and Taylor, W., pp.283–290 (1982), John Wiley & Sons., ISBN 0-471- 88954-7.
22) Brammer, A.J.: Threshold limit for hand-arm vibration Exposure throughout the workday. In *Vibration Effects on the Hand and Arm in Industry,* edited by Brammer, A.J. and Taylor, W., pp.291–301 (1982), John Wiley & Sons. ISBN 0-471-88954-7.
23) Futatsuka, M., Sakurai, T. and Ariizumi, M.: Preliminary evaluation of dose-effect relationships for vibration induced white finger in Japan. *Int. Arch. Occup. Environ. Health,* 54, 201–221 (1984).
24) Miura, T., Morioka, M., Kimura, K. and Isida, N.: On the occupational hazards by vibrating tools (Report III). *Reports of the Institute for the Science of Labour,* 52, 12–23 (1957).
25) Griffin, M.J.: Hand-arm vibration standards and dose-effect relationships. In *Vibration Effects on the Hand and Arm in Industry,* edited by Brammer, A.J. and Taylor, W., pp.259–268 (1982), John Wiley & Sons., ISBN 0-471-88954-7.
26) Brammer, A.J.: Dose-response relationships for hand-transmitted vibration: a preliminary evaluation. In *Hand-Arm Vibration,* edited by Okada, A., Taylor, W. and Dupuis, H., pp.231–335 (1990), Kyoei Press Company Limited, Kanazawa.
27) Brammer, A.J.: Thresholds for exposure of the hands to vibration. In *Proceedings of the 6th International Conference on Hand-arm Vibration,* edited by Dupuis, H., Christ, E., Sandover, J., Taylor, W. and Okada, A., pp.61–69 (1993), HVBG, D-53754 Sankt Augustin, ISBN 3-88383-331-2.