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Original Article

Frequency Weighting for Vibration-induced White Finger Compatible with Exposure-response Models

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Abstract: An analysis has been performed to derive a frequency weighting for the development of vibration-induced white finger (VWF). It employs a model to compare health risks for pairs of population groups that are selected to have similar health outcomes from operating power tools or machines with markedly different acceleration spectra (rock drills, chain saws, pavement breakers and motorcycles). The model defines the Relative Risk, $RR_{f(trial)}$, which is constructed from the ratio of daily exposures and includes a trial frequency weighting that is applied to the acceleration spectra. The trial frequency weighting consists of a frequency-independent primary frequency range, and subordinate frequency ranges in which the response to vibration diminishes, with cut-off frequencies that are changed to influence the magnitude of $RR_{f(trial)}$. The frequency weighting so derived when $RR_{f(trial)} = 1$ is similar to those obtained by other methods (W_{hf}, W_{hT}). It consists of a frequency independent range from about 25 Hz to 500 Hz (–3 dB frequencies), with an amplitude cut-off rate of 12 dB/octave below 25 Hz and above 500 Hz. The range is compatible with studies of vasoconstriction in persons with VWF. The results provide further evidence that the ISO frequency weighting may be inappropriate for assessing the risk of developing VWF.

Key words: Frequency weighting, Vibration white finger, Exposure-response models, ISO 5349, Relative risk

Introduction

Despite progress in quantifying the risk of developing vibration-induced white fingers (VWF) from exposing the hands to vibration, there remains uncertainty regarding the relative hazard posed by vibration at different frequencies[1–10]. The uncertainty is reflected in the diversity of exposure limits proposed for national and international standards[11]. The most commonly used procedures for assessing the risk of developing VWF, contained in Annexes to ISO 5349:1986[12] and ISO 5349–1:2001[13], are based on an idealized model in which the risk is predicted for a group of workers, each of whom is assumed to be performing essentially the same task involving vibration entering the hands[14–16]. The model, in common with others, relies on the assumption that the ongoing (e.g., daily) risk may be expressed, on a group basis, in terms of the group's mean daily exposure. This assumption has two important consequences: 1) only typical values for the magnitude of the vibration coupled to the hands and the duration of exposure need to be established for a population group, and; 2) all variability in human response to vibration exposure, arising from physical, biodynamic and individual factors[17], must be implied or expressed by other model parameters.

To construct the daily exposure, the magnitude of vibra-

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tion is first established from measurements of either the largest component acceleration in contact with the hand, or the vector sum of orthogonal acceleration components. The measurements are commonly performed when the source of vibration is used to undertake actual or simulated work either at the work place or in a laboratory setting. From these measurements an acceleration spectrum that reflects the work being performed is derived. For power tools that operate effectively in two modes – “on” and “off”, a single spectrum may be adequate to characterize the vibration experienced by the hand, and this was assumed in the original model. A summation of exposure elements containing different vibration magnitudes and spectra was subsequently introduced in the ISO procedures to estimate the daily exposure more precisely. In all cases the magnitude of each acceleration spectrum is frequency-weighted by a function that is presumed to account for the relative potential of accelerations at different frequencies to cause patho-physiological changes. Finally, “typical” daily vibration exposures are constructed from the frequency-weighted accelerations (either single axis component accelerations or the vibration total value) and exposure durations.

Studies of the prevalence or latency of VWF (i.e., time of exposure prior to the onset of white fingers) have reported agreement with the prediction of the health risk as well as overestimation and underestimation of the risk[18, 19)]. The health risk appears to be overestimated for power tools such as rock drills, pavement breakers, sand rammers and impact wrenches, (e.g., see references[2, 4, 20–23)], and underestimated for riveting tools and some grinders and chain saws (e.g., see references[24–26)]. The discrepancies, whether real or unsubstantiated[27)], have been attributed in the literature to one or more considerations used to characterize the exposure: 1) employing a frequency weighting function that progressively reduces the contribution to the hazard from accelerations at increasing frequencies; 2) restricting the upper frequency limit of the acceleration used to predict the hazard to 1400 Hz, and 3) ignoring temporal details of the acceleration waveform, such as the crest factor (e.g. impact or shock vibration).

While it is unrealistic to expect the ISO procedure to provide a precise prediction of the health risk for all exposure conditions, it is possible that the underlying model could be revised to improve its performance. In addition to the limitations revealed by epidemiologic studies, described above, the simplistic exposure-response model used in ISO 5349 may be criticized on additional grounds. Most notably, it is naive to expect a biological dose responsible for injury to be solely dependent upon the vibration exposure at a surface in contact with the hand without any dependence on the biodynamic response of tissues and the patho-physiological mechanisms causing localized peripheral vasospasms. Moreover, ignoring the temporal pattern of exposure implies an absence of recovery and healing mechanisms, which are the essence of a living, homeostatic biological system. It seems improbable that a single change to the model can resolve all these issues. Nevertheless, there are grounds for believing that a single change could significantly improve the prediction of risk for common percussive tools such as rock drills, and tools with low repetition rates such as pavement breakers or sand rammers. The belief stems from several considerations. Firstly, studies of lifetime exposure models that incorporate moderate day-to-day variations in exposure, as occur in the real world, and histories of daily exposures that diminish with time, which is equivalent to including a biologically plausible recovery mechanism, suggest that the lifetime exposure can be modelled as the product of the current daily exposure and a numerical constant (e.g., derived from the sum of successive daily exposures modified by an exponential decay rate)[28, 29)]. Secondly, recent attempts to model the development of VWF using alternate exposure expressions have found that vibration without any frequency weighting provides a better fit to the data than the frequency weighting employed in the ISO model[30, 31)]. Thirdly, restriction of the upper frequency limit of the analysis to 1400 Hz has been shown to be inconsequential to predicting the onset of VWF in rock drills[4)], and hence more generally for frequency weightings that progressively reduce the contribution to the hazard from increasing frequencies. Fourthly, re-examination of the frequency weighting to include higher frequencies, as considered here, does not necessarily exclude the high frequency components of the stimulus that will be responsible for the crest factor or “impulsiveness” of the source of vibration, though the phase relations responsible for the time history of tissue displacements will not be included.

Accordingly, the purpose of this paper is to explore the application of alternative formulations of the contribution of vibration at different frequencies to the prediction of the onset of white fingers. The procedures described in ISO 5349:1986 and ISO 5349:2001 and their underlying models will serve as the basis for the analysis. The procedures employ versions of the model that differ only in the details of the frequency weightings and other scaling factors. The original model, as incorporated into Annex A of ISO 5349:1986, employed the dominant acceleration component of a surface in contact with the hand as the basis for the assessment (i.e., the component with the largest magnitude). The exposure is expressed in terms of a daily, energy-averaged acceleration that is reported for a nominal four-hours' of exposure. The model employed in ISO 5349-1:2001 extends the evaluation of the vibration entering the hands to all three vector components, in circumstances in which these can be determined, and computed the eight-hour energy equivalent daily exposure. Both procedures predict the duration of exposure in years before the onset of finger blanching in a vibration-exposed population group.

In this paper, the specification of trial frequency weightings is first considered by introducing primary and subordinate frequency ranges. The former encompasses the frequencies at which the health effect of interest occurs from least exposure to vibration, and its probable form is deduced from studies most relevant to the development of VWF. Frequencies forming the upper and lower boundaries of the primary frequency range define the transitions to the subordinate frequency regions. The relative risk of developing VWF for two population groups operating different power tools or machines is then expressed in terms of parameters that characterize the daily exposure, which include the trial frequency weighting. In order to compare the performance of different trial frequency weightings, studies must be found in which population groups operated tools or machines with markedly different vibration frequency spectra. The analysis is performed separately for upper and lower subordinate frequency ranges, and for single axis and triaxial (vibration total value or vector sum) acceleration spectra.

Methods

Form of trial frequency weightings

There are an unlimited number of trial frequency weightings that could be proposed. Each may be divided into a primary frequency range, or ranges, where the health effect of interest results from least acceleration magnitude, and two, or more, subordinate frequency ranges in which the health effect diminishes with changes in the frequency content of the vibration. An example of the simplest trial frequency weighting is shown in Fig. 1.

It consists of a single primary frequency range and one upper and one lower subordinate frequency ranges. The primary frequency range extends to the −3 dB cut-off frequency of the subordinate frequency ranges.

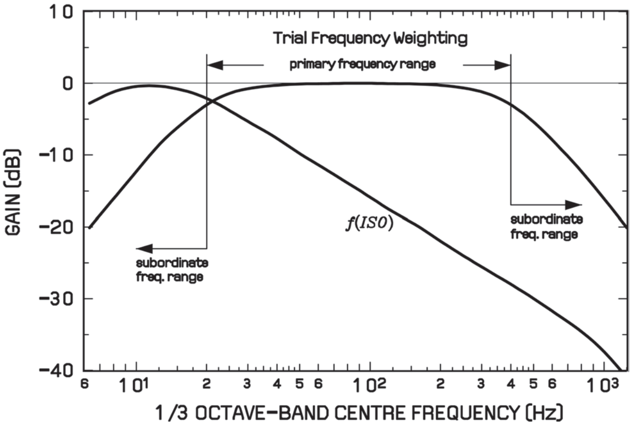

Fig. 1. Trial frequency weighting showing the primary frequency range and subordinate frequency ranges. The ISO frequency weighting, W_h in ISO 5349-1:2001, is shown for comparison, labelled *f*(*ISO*).

Equinoxious contours, considered here as contours of vibration magnitude at different frequencies that result in the same, or equivalent, physiological or patho-physiological responses, can provide the essential biological information on which to base a trial frequency weighting. However, it is difficult to inter-relate the results from different investigations of physiological responses unless the biodynamic coupling between the source of vibration and the surface of the hand is similar. Moreover, the relationship between the results of laboratory experiments and occupational exposures to vibration remains unclear. The results of animal experiments involving either physiological or pathological changes introduce the additional uncertainty of interspecies differences. For these reasons, attempts to construct frequency weightings for VWF from physiological responses or animal studies, while informative, (see, for example, reference 14) are not expected to be definitive.

Given the limitations of laboratory and animal studies, a synthesis of results selected for their relevance to the development of VWF would seem necessary to inform the choice of a trial frequency weighting. This is applied here to the primary frequency range, where the health effect of interest occurs with least vibration magnitude, that is, where vibration is most noxious. Pyykkö and co-workers have demonstrated that the threshold for producing "strong vasoconstriction" in the fingers of persons with VWF is approximately independent of acceleration magnitude at frequencies of 60, 100, 200 and 400 Hz, but somewhat less acceleration was required at 30 Hz[32]. The frequencies that most commonly produced vasoconstriction in these workers were 80 and 125 Hz, suggesting that the more sensitive response to vibration provoked less often at 30 Hz may have been an outlier. These results have not been replicated with healthy subjects[33–37], which suggests there are patho-physiological differences between the fingers of persons suffering from VWF and those of healthy persons[38]. Confirmation of pathological changes in the vasculature of the fingers of persons with VWF has been provided by Takeuchi and co-workers[39]. Thus, from these results, the most noxious frequencies for VWF would appear to be from 80 to 125 Hz, and the form of the equinoxious contour would appear to be frequency independent within, and somewhat beyond, this primary frequency range. There does not appear to be a second primary frequency range for VWF. This description of the form and extent for the primary frequency range of the trial frequency weighting is compatible with the transmission of vibration to the fingers[7], and with predictions from biodynamic models of the hand and fingers for energy absorption in tissues[40]. It is also compatible with the frequencies considered the most likely to lead to VWF in an analysis of epidemiologic data conducted by Tominaga[8].

There is, unfortunately, no information from VWF sufferers on the form of the equinoxious contour outside the primary frequency range. Thus there is little on which to base the form of the two subordinate frequency ranges in which the health effect diminishes with changes in the frequency content of vibration. For this reason, there seems to be little merit in exploring different rates of change of the equinoxious function with frequency. Moreover, the only study in which this has been attempted was inconclusive [8]. Accordingly, the form of the frequency weighting in the subordinate frequency ranges will be assumed to follow that implied by the band limiting filters incorporated into the current ISO standard (i.e., 12 dB/octave). This has the additional benefit of the trial frequency weighting becoming identical to that of the band-limiting filter in ISO 5349–1:2001 when the primary frequency range extends to the band-limiting filter frequencies (i.e., −3 dB frequencies of 6.3 and 1250 Hz). Recent analyses of epidemiologic data have suggested this frequency weighting is a better predictor of the cumulative incidence of VWF than that in the current international standard[9, 31]. Several studies have also advocated the use of this so-called “frequency-unweighted acceleration” for assessing the risk of developing VWF[2, 30, 41].

Construction of trial frequency weightings

As the form of the equinoxious contour for the development of VWF is taken to be frequency independent in the primary frequency range, trial frequency weightings have been constructed by selecting different upper and lower frequency limits for the primary frequency range. The limits are selected without reference to previous work. The analysis is conducted separately, that is, the consequences of adjusting the upper frequency limit are first explored and a best fit to the data obtained. The consequences of adjusting the lower frequency limit are then considered. The vibration of all power tools and machines included in the analysis has been expressed in terms of one-third octave-band frequency spectra. The spectra are either from previously published studies of power tools and the development of VWF, or from unpublished data provided to the authors. In each case the source is identified.

The trial frequency weighting is applied to the dominant single-axis acceleration spectrum if this vibration component was reported in the study. For studies in which all three orthogonal acceleration components spectra were reported, the vector sums of the three components are included in a three-axis analysis.

Comparison of two population groups with the same risk of developing VWF

In order to compare different frequency weightings, population groups must be found with similar prevalence and latency of VWF that operate power tools or machines with vibration spectra dominated by accelerations at markedly different frequencies. In these circumstances, a direct comparison can be made between trial frequency weightings provided the exposure in each population group can be characterized by a single exposure rate, that is each person performed essentially the same tasks with the same type of power tool or machine. These requirements severely restrict the number of studies that can qualify for the analysis. In addition, epidemiologic data from small population groups are excluded. The size restriction is imposed, as in the original exposure-response model[14, 16], in an attempt to avoid errors introduced by possibly unrepresentative population groups.

The limitations on population groups and exposures restrict the analysis, at the present time, to cross-sectional epidemiologic studies of vibration-exposed workers. Such studies are unable to control the rates at which persons enter and leave the workforce. Consequently, changes in group membership may influence both the prevalence and latency of VWF. Additionally, the raw prevalence needs to be adjusted for the background prevalence of white fingers in a non-exposed control group. In view of such uncertainties, it has been found preferable to predict the mean group latency of VWF, t_{LI}, from the single exposure rate that is used to characterize the vibration exposure of the group, $a_{f(trial)}$. The latter will depend on the (trial) frequency weighting employed, $f(trial)$. For the ISO frequency weighting, $f(ISO)$ shown in Fig. 1, the group latency (in years) may be expressed as[4]:

$$t_{LI} = 165 / [a^2_{f(ISO)} t_d]^{0.535} \tag{1}$$

where t_d is the daily duration of exposure (in hours) and the acceleration is expressed in units of metres per second squared. Then, for two population groups that have exposures characterized by ISO frequency-weighted accelerations of $a(1)_{f(ISO)}$ and $a(2)_{f(ISO)}$, respectively, and identical latencies:

$$a(1)^2_{f(ISO)} t(1)_d = a(2)^2_{f(ISO)} t(2)_d \tag{2}$$

This equation implies an equal risk of developing VWF in two population groups when their exposure is assessed using the ISO 5349 frequency weighting. The frequency weighting gives most emphasis to frequencies around 10 Hz while progressively reducing the contributions to $a_{f(ISO)}$ as frequency increases (see Fig. 1).

Relative Risk of developing VWF in two population groups

When there is not an equal risk of developing VWF in two population groups, then from equation (1) the risk for persons in group 1, $R(1)_{f(ISO)}$, can be expressed in terms of the risk for persons in group 2, $R(2)_{f(ISO)}$ by:

$$\begin{aligned} R(1)_{f(ISO)} / R(2)_{f(ISO)} &= t(2)_{LI} / t(1)_{LI} \\ &= \left([a(1)^2_{f(ISO)} t(1)_d] / [a(2)^2_{f(ISO)} t(2)_d] \right)^{0.535} \end{aligned} \tag{3}$$

In this way the risk of developing VWF in the two population groups has been expressed in terms of parameters applicable to the different daily exposures. It should be noted that forming equation (3) has eliminated the empirical multiplying constant in equation (1) and so removed any issue regarding uncertainty in its magnitude. The exponent, however, remains. In practice it is unlikely that true group mean latencies can be obtained from cross-sectional epidemiological studies, and so equation 3 must be considered an approximation when applied to real-world data.

While the ratio of accelerations produced by power tools and machines can be calculated for any frequency weighting, the interpretation in terms of the risk of developing VWF contained in equation (3) has been derived from a model employing the ISO frequency weighting. It is not evident that equation (3) would be applicable if other frequency weightings, such as the trial frequency weighting shown in Fig. 1, were employed. Equation (3) may, however, be expressed as:

$$R(1)_{f(ISO)} / R(2)_{f(ISO)} = \left(\frac{a(1)_{f(ISO)}}{a(2)_{f(ISO)}} \right)^{1.07} \left(\frac{t(1)_d}{t(2)_d} \right)^{0.535} \tag{4}$$

Hence only the first term containing the ratio of the tool accelerations is subject to the frequency weighting, and its exponent in the expression is close to unity (1.07). Griffin and co-workers have explored the application of alternative exposure expressions for predicting the onset on VWF and conclude from their data that the risk is somewhat better predicted by the frequency-unweighted acceleration (i.e., employing only the band-limiting filters of ISO 5349:2001) than the ISO frequency-weighted acceleration[30]. In each case they found the product of the acceleration (either frequency weighted or unweighted) and total lifetime exposure duration, rather than a higher power of acceleration, provided the best agreement with the epidemiologic data. While their approach is somewhat different from that employed here, which focuses on daily exposures, it does suggest it is reasonable to assume initially the form for the risk ratio contained in equation (4) for other frequency weightings. In particular, the exponent for the accelerations in equation (4) is expected to be close to unity, but its precise value remains unknown and may differ between frequency weightings. Accordingly, to estimate the risk of developing VWF for an arbitrary trial frequency weighting, it would appear prudent to impose the following restrictions on the analysis: simplify the exponents in the expressions for the acceleration ratio and exposure duration and, simultaneously, restrict detailed interpretation of risk to a given trial frequency weighting and comparatively small deviations from unity in order to mitigate uncertainty in the value of the exponents. Thus for arbitrary frequency weightings equation (4) becomes:

$$\begin{aligned} RR_{f(trial)} &= \left(R(1)_{f(trial)} / R(2)_{f(trial)} \right)^{x(trial)} \\ &= \left(\frac{a(1)_{f(trial)}}{a(2)_{f(trial)}} \right) \left(\frac{t(1)_d}{t(2)_d} \right)^{1/2} \end{aligned} \tag{5}$$

where $RR_{f(trial)}$ describes the Relative Risk of developing VWF in population group 1 compared to group 2 for an arbitrary frequency weighting, and $x(trial) \approx 1$.

It should be noted that equation (5) is valid for all values of latency provided the *ratio* of the latencies for the two population groups remains close to unity. Consequently, the expression will apply to population groups with vibration exposures resulting in near infinite latency, that is,

Table 1. Epidemiologic data for studies of jack-leg rock drillers and chain saw operators with similar mean latency of VWF

Population Group	Ref.	N_{exp}	Observed Latency (yr)	Observed Prevalence (%)	Dominant Single-Axis ISO Acceleration (m/s^2)	Vector Sum ISO Acceleration (m/s^2)	Observed Daily Exposure Duration (h)
Rock drillers (Brubaker *et al.*)	42	58	7.2 ± 6.9	45	32	–	1.5
	43		–	–	14	–	–
Rock drillers (Pelmear *et al.*)	44	143	10.4	43	–	–	2.1
	45		–	–	17	–	
	2		–	–	22	–	
Rock drillers (Keith & Brammer)	4	–	–	–	18 ± 2	22.4	–
Summary of Rock Drill Data		**201**	**9.5**	**43**	**17.4**	**22.4**	**1.9**
Chain Sawing (Bovenzi *et al.*)	46	65	9.4 ± 6.8	29	–	–	–
	47		–	–	7.2	9.1	4.4
Summary of Chain Saw Data		**65**	**9.4**	**29**	**7.2**	**9.1**	**4.4**

groups in which the raw prevalence of white fingers does not exceed, or only marginally exceeds, that of an unexposed control population. Also, as is the case for the risk ratio of equation (3), the relationship must be considered an approximation when applied to real-world data from cross-sectional epidemiologic studies.

Results

Upper cut-off frequency for the primary frequency range

A search has been conducted to find population groups reporting similar prevalences and latencies of VWF consisting of more than 30 persons and with the following characteristics: within each group all subjects perform essentially the same work with the same power tools or machines, and across groups the workers operate power tools or machines with vibration spectra dominated by accelerations at markedly different frequencies that may be characterized by single exposure rates. As already noted, these requirements severely restrict the number of studies that qualify for the analysis. There are only nine studies involving two types of power tools that, together, fulfil the requirements and from which sufficient epidemiologic data and acceleration spectra can be derived to lend credibility to the analysis[2, 4, 42–47]. The epidemiologic data from these studies are summarized in Table 1, and involved either miners operating rock drills or forest workers harvesting trees with chain saws. The former are a composite of studies of hard-rock mining in Canada. The contemporary epidemiologic data and detailed vibration measurements derived from various sources, when combined, provide a complete picture of the consequences of hard-rock mining using the ubiquitous pneumatic jack-leg drill, the design of which has not changed for over a century. The chain saw vibration was measured when cross-cutting wood following an established test procedure[48], and the published data have been supplemented by personal correspondence. The number of persons in each population group is N_{exp}.

Inspection of Table 1 confirms that the mean VWF latencies for exposure to the two types of power tools were similar in these studies. Additionally, the raw prevalences of VWF are comparable (43% for the rock drillers and 29% for the chain sawyers), and substantially above the background prevalence of white fingers in the general population (typically from about 2 to 10%)[49]. However, the dominant single-axis component accelerations for the two power tools differ substantially when frequency weighted according to the ISO frequency weighting (viz., 17.4 m/s^2 for rock drills versus 7.2 m/s^2 for chain saws). The same observation applies to the vector sum accelerations. Reference to equations (1) and (2) reveals that even when the daily exposure durations are included, a model employing the ISO frequency weighting will not predict an equal risk of developing VWF for these populations groups (equation (2)), or similar latency (equation (1)).

Adjustment of the upper frequency limit is not expected to reduce the inconsistency, and this is confirmed by the results in Table 2. In this Table the risk of developing VWF from operating the rock drill is expressed relative to that from operating the chain saw for different upper cut-off frequencies (column 1) applied to the component accelerations (columns 2 and 4). The magnitudes of the numerators and denominators of the Relative Risk computed using the ISO frequency weighting are shown

Table 2. Effect of adjusting the upper cut-off frequency on the risk of developing VWF for the ISO frequency weighting, *f*(*ISO*), shown in Fig. 1. The lower cut-off frequency is 6.3 Hz

-3 dB Cut-Off Frequency (Hz)	Rock Drill		Chain Saw		Risk	
	Component Acceleration (m/s^2)	$a(1)_{f(ISO)}\ (t_1)^{1/2}$ (m/s$^{1.5}$)	Component Acceleration (m/s^2)	$a(2)_{f(ISO)}\ (t_2)^{1/2}$ (m/s$^{1.5}$)	Risk Ratio Equation (4)	Relative Risk Equation (5)
1250*	17.4	1440	7.2	912	1.6	1.6
1000	17.4	1440	7.2	912	1.6	1.6
800	17.2	1420	7.2	912	1.6	1.6
630	17.0	1400	7.2	912	1.6	1.5
500	17.0	1400	7.2	912	1.6	1.5
400	16.8	1390	7.2	912	1.6	1.5
315	16.8	1390	7.2	912	1.6	1.5

*Frequency weighting W_h in ISO 5349-1:2001.

for different cut-off frequencies (columns 3 and 5). The value of the risk ratio (equation (4)) is given as well as the Relative Risk (equation (5)). Note that the first row of Table 2 employs the upper limiting frequency specified for the frequency weighting in the International Standard and so provides results for W_h[13]. The subsequent rows provide results for an ISO frequency weighting that has been progressively truncated at the upper frequencies listed in column 1. Inspection of Table 2 shows that only an insignificant change in either the risk ratio or Relative Risk is introduced even when the upper frequency limit is reduced by three quarters (i.e., from 1250 to 315 Hz). Under all these conditions, employing the ISO frequency weighting as the "trial" frequency weighting in the model results in predicting the risk of developing VWF for the miners operating rock drills to be much greater than that for the forest workers operating chain saws (i.e., 1.5–1.6), in conflict with the epidemiologic data.

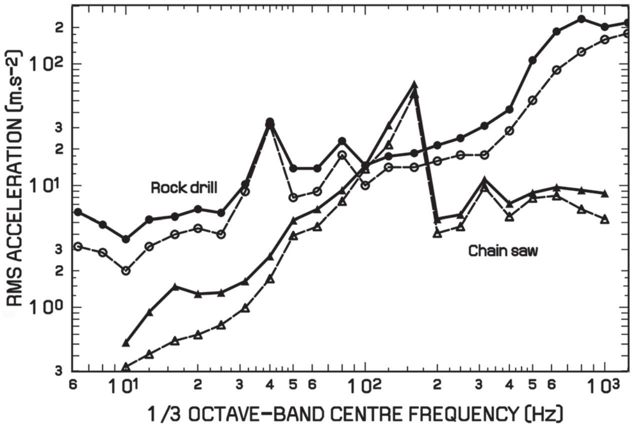

Fig. 2. One-third octave band frequency spectra of rock drill (circles) and chain saw (triangles) handle accelerations: open symbols − dominant single-axis accelerations; filled symbols − acceleration vector sums (3-axes). For sources of data see text.

Typical one-third octave band frequency spectra for the two power tools are shown in Fig. 2 for the dominant component accelerations and triaxial (vector) acceleration sums[4, 47]. The former are shown by open symbols (circles and triangles for rock drills and chain saws, respectively), and the latter by closed (filled) symbols. Inspection of this diagram reveals that the power tools contain components that differ markedly in magnitude at almost every frequency. The peak of the chain saw acceleration spectrum occurs at about 160 Hz while that of the rock drill spectrum occurs at about 800 Hz. Consequently, introducing a trial frequency weighting with a primary frequency range that is frequency independent (e.g., see Fig. 1) can be expected to influence dramatically estimates of Relative Risk.

The results of this analysis are summarized for the component accelerations in Table 3, for a trial frequency weighting consisting of a flat primary frequency range with an adjustable upper cut-off frequency. Reference to the frequency spectra in Fig. 2 confirms that reducing the upper frequency limit of the primary frequency range will reduce the frequency-weighted component acceleration of the rock drill much more than that of the chain saw, and leads to a progressive reduction in the Relative Risk (column 6). The model predicts that the Relative Risk of using the rock drill compared to the chain saw will be equal when the primary frequency range of the trial frequency weighting extends from 6.3 to 500 Hz. Close inspection of the Relative Risk as a function of cut-off frequency reveals that $RR_{f(trial)}$ changes rapidly with frequency when the Relative Risk is close to unity, providing clear definition of the upper frequency limit for the primary frequency range. The ability to define the upper frequency limit stems from the very different rates of change of acceleration with frequency at 500 Hz for the two power tools

Table 3. Effect of adjusting the upper cut-off frequency of the primary frequency range of the trial frequency weighting on the Relative Risk for the dominant acceleration component. The lower cut-off frequency is 6.3 Hz

-3 dB Cut-Off Frequency (Hz)	Rock Drill		Chain Saw		Relative Risk $RR_{f(trial)}$
	Component Acceleration (m/s^2)	$a(1)_{f(trial)}\ (t_1)^{1/2}$ (m/s$^{1.5}$)	Component Acceleration (m/s^2)	$a(2)_{f(trial)}\ (t_2)^{1/2}$ (m/s$^{1.5}$)	
1250	282	22000	66.1	8320	2.6
1000	234	19000	66.1	8320	2.3
800	200	15600	66.1	8320	1.9
630	141	11800	65.3	8220	1.4
500	100	8340	64.6	8130	1.0
400	89.1	6960	64.6	8130	0.86
315	70.8	5660	63.8	8030	0.70

Table 4. Effect of adjusting the upper cut-off frequency of the primary frequency range of the trial frequency weighting on the Relative Risk for the vector sum acceleration. The lower cut-off frequency is 6.3 Hz

-3 dB Cut-Off Frequency (Hz)	Rock Drill		Chain Saw		Relative Risk $RR_{f(trial)}$
	Vector Sum Acceleration (m/s^2)	$a(1)_{f(trial)}\ (t_1)^{1/2}$ (m/s$^{1.5}$)	Vector Sum Acceleration (m/s^2)	$a(2)_{f(trial)}\ (t_2)^{1/2}$ (m/s$^{1.5}$)	
1250	417	34500	81.3	10200	3.4
1000	376	31100	81.3	10200	3.0
800	313	25900	80.4	10100	2.6
630	245	20300	80.4	10100	2.0
500	184	15200	79.4	10000	1.5
400	138	11400	79.4	10000	1.1
315	107	8860	78.5	9880	0.90

(see Fig. 2). Note that this property of the tools' vibration spectra is inconsequential if the ISO frequency weighting is employed (i.e., compare results in column 7 of Table 2 with those in column 6 of Table 3).

A similar observation may be made if triaxial accelerations are used to characterize the tools' vibrations. The results of the analysis are shown in Table 4. Once again, inspection of the Relative Risk as a function of cut-off frequency reveals that $RR_{f(trial)}$ changes rapidly with frequency when $RR_{f(trial)} \approx 1$, providing clear definition of the upper frequency limit for the primary frequency range of this trial frequency weighting (see column 6 of Table 4). In this case the model predicts that the Relative Risk of using the rock drill compared to the chain saw will be equal when the primary frequency range of the trial frequency weighting extends from 6.3 to between 315 and 400 Hz. Reference to the frequency spectra of Fig. 2 reveals that the triaxial acceleration sums for the rock drill increase more rapidly than the corresponding single axis values at frequencies from 400 Hz to 800 Hz, leading to contributions to $RR_{f(trial)}$ that result in a lower frequency limit for the trial frequency weighting. This observation serves to illustrate the sensitivity of predictions of $RR_{f(trial)}$ to the detailed characteristic of tool vibration spectra and hence the potential for over-interpreting the precision of the upper cut-off frequency derived from this analysis. Nevertheless, the model does indicate that a trial frequency weighting consisting of the so-called frequency-unweighted acceleration with an upper cut-off frequency of 1250 Hz (shown in row 1 of Tables 3 and 4) will substantially overestimate the Relative Risk of developing VWF in these populations of rock drillers (i.e., $RR_{f(trial)} \sim 2.6 - 3.4$).

Lower cut-off frequency for the primary frequency range

A search has been conducted for suitable population groups exposed to hand-transmitted vibration to permit a similar analysis to be performed to that described above, to establish the lower frequency limit of the trial frequency weighting. No studies have been found that fulfil the requirements. There are, however, studies that describe exposures close to the threshold for the onset of VWF, which may be considered here as they possess raw prevalences of white finger that do not exceed those of control populations. Thus the latent intervals for the population groups,

Table 5. Epidemiologic data from studies of users of pavement breakers in the gas industry and postmen riding motorcycles with the same prevalence of VWF as controls

Population Group	Ref.	N_{exp}	Observed Prevalence (%)		Dominant Single-Axis ISO Acceleration (m/s^2)	Vector Sum ISO Acceleration (m/s^2)	Observed Daily Exposure Duration (h)
			Exposed	Controls			
Pavement breakers	21	895	9.6	9.5	–	–	–
	51		–	–	17.7	–	0.5–2
	52		–	–	17.9	–	–
Summary of Breaker Data		**895**	**No VWF**		**17.9**	**–**	**0.5–2**
Motorcycles (Postmen) (“short distance” group)	53	8773	1.9	0.9 – 1.7	≤ 2.1	–	3.1
Motorcycle (“old type” at 51 km/h)	54				2.1		
Summary of Motorcycle Data		**8773**	**No VWF**		**2.1**	**–**	**3.1**

while usually unknown, may be expected to approach a working lifetime, and so will satisfy the condition required for applying equation (5), namely that the ratios of the latencies will be close to unity. Nevertheless, in view of the need to distinguish small increases in prevalence of white fingers from that of a control group, it would appear prudent to increase the minimum group size to, say, 400 persons. This group size is estimated to permit a difference in prevalence of 0.1% to be detected with 95% confidence in a two-sided test[50], and assumes that the standard deviation for the prevalence of Raynaud’s phenomenon in population studies is 1% (see, for example, reference 49). There are two well-documented exposures that may then be considered, one of which contained a “low” and “high” exposed subgroup[21, 51–54]. The epidemiologic data for these populations are summarized in Table 5, and involved either gas maintenance/construction workers operating pavement breakers or postmen delivering mail by motorcycle. Data for the “low” exposure subgroup are listed for the motorcycle riders.

Reference to Table 5 confirms that the number of exposed workers in each group (N_{exp}) exceeded the suggested minimum. For both these groups the observed raw prevalence of white fingers was indistinguishable from that of a control group (columns 4 and 5). For each of these work situations, there are reasons to believe that the exposures are close to the threshold for the onset of VWF. For the gas workers, cases of VWF have been reported for this work elsewhere[55], suggesting that the lower extreme of the daily exposure should be used here for estimates of Relative Risk. Similarly, for the postmen, there was a “high” exposure subgroup in which a greater incidence of white fingers was detected consistent with the development of VWF (data not included in Table 5)[53].

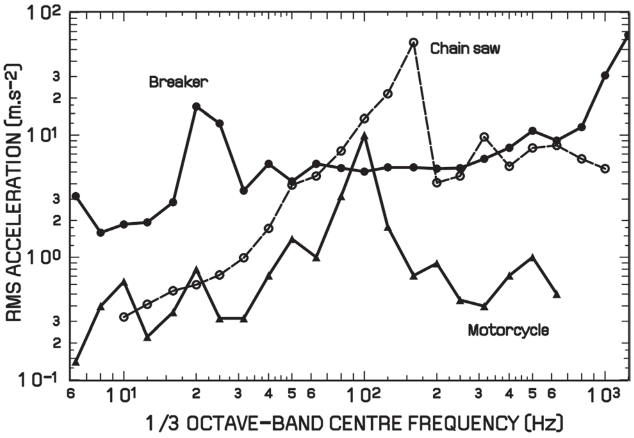

Fig. 3. One-third octave band frequency spectra of the dominant single-axis handle acceleration of a pavement breaker (filled circles), motorcycle (triangles) and chain saw (open circles). The chain saw spectrum is from Fig. 2. For sources of data see text.

Typical one-third octave band frequency spectra for the pavement breaker and motorcycle handle vibration are shown in Fig. 3 for the dominant component accelerations[52, 54]. The former is shown by the filled circles and the latter by the filled triangles. Also shown for comparison is the dominant component acceleration of the chain saw handle employed in the analysis of the upper frequency limit of the trial frequency weighting (open circles and dashed line). Inspection of this diagram reveals that the pavement breaker and motorcycle handle vibration spectra contain components that differ markedly in magnitude at almost every frequency. The peak of the motorcycle acceleration spectrum occurs at about 100 Hz while the pavement breaker spectrum possesses two peaks, one at about 20 Hz and a second at about 1250 Hz. Consequently, introducing a trial frequency weighting with a

Table 6. Effect of adjusting the lower cut-off frequency of the primary frequency range of the trial frequency weighting on the Relative Risk for the dominant acceleration component

-3 dB Cut-Off Frequencies (Hz)	Pavement Breaker		Motorcycle		Relative Risk $RR_{f(trial)}$
	Component Acceleration (m/s^2)	$a(1)_{f(trial)}\,(t_1)^{1/2}$ ($m/s^{1.5}$)	Component Acceleration (m/s^2)	$a(2)_{f(trial)}\,(t_2)^{1/2}$ ($m/s^{1.5}$)	
6.3–1250	70.8	3040	11.1	1160	2.6
6.3–500	31.6	1410	11.1	1160	1.2
16–500	31.6	1400	11.0	1150	1.2
20–500	31.6	1300	11.0	1150	1.1
25–500	28.2	1200	11.0	1150	1.0
31.5–500	28.2	1140	11.0	1150	1.0
40–500	25.1	1090	11.0	1150	0.95
50–500	25.1	1050	11.0	1150	0.91

primary frequency range that extends to the upper cut-off frequency derived above, namely 500 Hz for single axis vibration, will reduce the contribution from the highest frequencies of the pavement breaker spectrum to $RR_{f(trial)}$. Under these circumstances, estimates of Relative Risk will be influenced primarily by increases in the lower cut-off frequency.

The results of this analysis are summarized in Table 6. Reference to the frequency spectra in Fig. 3 confirms that increasing the lower frequency limit of the primary frequency range will initially reduce the frequency-weighted component acceleration of the pavement breaker much more than that of the motorcycle (i.e., compare columns 2 and 4 of Table 6), and leads to a progressive reduction in the Relative Risk (column 6). The model predicts that the Relative Risk of using the pavement breaker compared to the motorcycle will be equal when the primary frequency range of the trial frequency weighting extends from 25, or 31.5, to 500 Hz. Close inspection of the Relative Risk as a function of cut-off frequency reveals that $RR_{f(trial)}$ changes slowly with frequency when the Relative Risk is close to unity.

The upper cut-off frequency of the primary frequency range employed in this analysis has so far been that derived from dominant component accelerations. A somewhat different upper cut-off frequency has been derived above from the analysis of the triaxial vector sum accelerations (between 315 and 400 Hz). Accordingly, the analysis to determine the lower frequency limit of the primary frequency range has been repeated with the upper cut-off frequency set to 400 Hz. The influence on the Relative Risk from changing the lower cut-off frequency when the upper cut-off frequency is set to 400 Hz is shown in Fig. 4. The graph displays the Relative Risk (ordinate) as a function of the lower cut-off frequency, calculated at one-third octave band centre frequencies from 6.3 to 63 Hz (abscissa). In this diagram comparable results for an upper cut-off frequency of 500 Hz are also included (from Table 6). It can be seen from Fig. 4 that the two upper cut-off frequencies define a range of lower cut-off frequencies for the primary frequency range from 20 Hz to 31.5 Hz (i.e., when $RR_{f(trial)} = 1$).

Specification of frequency weighting for developing VWF

A frequency weighting applicable to the onset of VWF may now be specified by combining the results of the analyses. The function is obtained by applying the lower and upper frequency limits derived above to the primary frequency range of the trial frequency weighting and is shown in Fig. 5. It should be noted that applying the lower frequency limit to the data of Tables 3 and 4 does not change the upper frequency limits derived by the analysis.

Uncertainties in the values of the lower and upper frequency limits for the primary frequency range dictate the form of the presentation. In this diagram the frequency weighting for developing VWF derived by the analysis described here is shown by filled circles. It can be seen from Fig. 5 that whereas the frequency weighting can be uniquely defined at frequencies from 50 to 160 Hz (corresponding to the centre of the primary frequency range), ambiguity in the specification of the cut-off frequencies leads to a band of frequencies for both the upper and lower subordinate frequency ranges. Consequently, the frequency weighting is shown by two filled circles for each gain, delineating the range of acceptable frequencies derived from this analysis. Frequency weightings proposed recently elsewhere for the development of VWF are also shown in this diagram for comparison[56)]. The dash-dot line is derived from a biodynamic analysis of the energy coupled into the finger from contact with a vibrating sur-

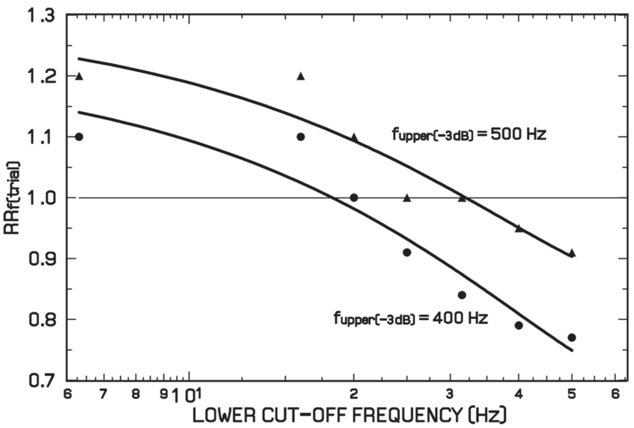

Fig. 4. Risk of developing VWF for users of pavement breakers in the gas industry relative to that of postmen riding motorcycles. The relative risk ($RR_{f(trial)}$) is shown as a function of the lower (−3 dB) cut-off frequency for trial frequency weightings with upper cut-off frequencies of 400 or 500 Hz. Data for 400 Hz cut-off shown by circles, and 500 Hz by triangles. The lines are best fits to the data.

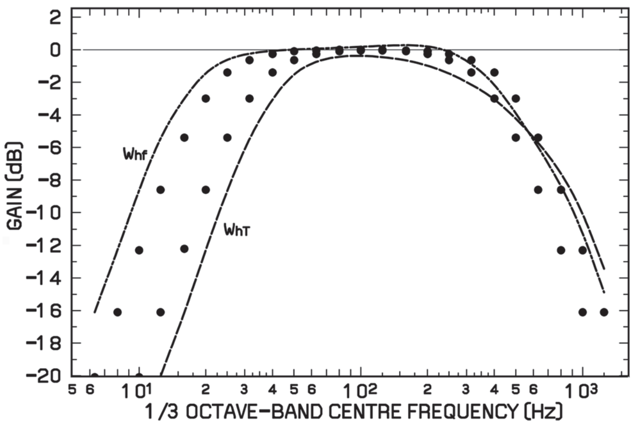

Fig. 5. Comparison of the preferred trial frequency weighting (between filled circles) with frequency weightings W_{hT} and W_{hf}.

face (W_{hf}), and the dashed line is derived from an analysis of epidemiologic data (W_{hT}).

Discussion and Conclusions

The analysis described here to derive a frequency weighting for the onset of VWF employs a model to compare the health risks for pairs of population groups operating power tools or machines whereby vibration enters the hands. The model is based on the ISO frequency weighting and is extended to arbitrary frequency weightings. This has been done by introducing the Relative Risk, which may be defined precisely for the ISO frequency weighting but includes an unknown index, $x(trial)$, when other frequency weightings are employed. By constructing the analysis so that only values of $RR_{f(trial)}$ close to unity are of significance and restricting interpretations to the same trial frequency weighting, uncertainty in the magnitude of $x(trial)$ is mitigated. Confidence in the extension of the analysis from the ISO weighting to a general weighting, that is, from applying equation (4) to applying equation (5), can be obtained from the similarity of the estimates of risk by the two equations in Table 2 (columns 6 and 7) as well as from the exploration of other descriptions of vibration exposure reported elsewhere[30)].

The definition of a trial frequency weighting consisting of a primary frequency range and subordinate frequency ranges is one of necessity. There is no simpler definition that could be employed. While a description of the primary frequency range as frequency independent when expressed in terms of acceleration might appear overly simplistic, it is based on the most convincing patho-physiological evidence, namely the induction of vasoconstriction by vibration in persons suffering from VWF[32)]. A common precipitator of vasospasm in persons suffering from VWF is exposure to cold temperatures, but the exposure by itself does not inform the choice of trial frequency weighting. Studies of vasoconstriction induced by vibration, body cooling and loud noise were included in the laboratory experiments that confirmed the frequency independence of the primary frequency range[32)]. In addition, it should be noted that the boundaries of the primary frequency range have been determined by the analyses described in this paper and not by prior selection or reference to the patho-physiological experiments.

Finding epidemiologic studies of vibration-exposed population groups that comply with all the requirements for the analysis, namely groups of sufficient size with similar prevalence and latency of VWF that operate power tools or machines with vibration spectra dominated by accelerations at markedly different frequencies in which exposures can be characterized by single exposure rates (i.e., each person in a population group performed essentially the same tasks with the same type of power tool or machine), presented a daunting task. Searches were performed using Medline, as well as off-line (e.g., books, papers, reports, conference proceedings, and personal communications). A separate search was conducted of the Japanese literature. The results have all been considered for this analysis. The inclusion/exclusion criteria for the analysis, summarized above, have been introduced in the *Methods* and their application to specific pairs of studies necessary to satisfy the condition $t(2)_{LI} / t(1)_{LI} \rightarrow 1$ is described in the *Results*. Great care has been taken to ensure that the epidemiologic and exposure data, and the vibration measurements were obtained from reliable contemporary sources. The spectral characteristics of the power tools are supported by measurements conducted by the authors.

The derivation of the upper frequency limit of the trial frequency weighting depends on the accuracy of the epidemiologic data summarized in Table 2 as well as the acceleration spectra shown in Fig. 2. There is little doubt that the rapidly increasing acceleration with frequency of the rock drill spectrum permits a clear definition of the upper frequency limit for the primary frequency range. The careful attention to the accuracy of the rock drill vibration measurements, described in detail in the source publication, provides confidence that the acceleration spectra are representative of the vibration of the pneumatically-powered rock drills employed in hard rock mining at the time of the epidemiologic surveys. The chain saw vibration spectra are typical of those recorded elsewhere. Thus, errors in the vibration measurements are unlikely to provide a reason to discount the upper frequency limit derived from the analysis.

A large population of exposed persons was prescribed for the derivation of the lower frequency limit of the trial frequency weighting. The need to resolve differences in prevalence as small as 0.1% in order to establish the threshold for the onset of VWF led to this requirement. The gas industry controls, however, were not manual workers but persons working outdoors reading gas meters or collecting charges for gas delivery[21], and hence their suitability for a control group may be challenged. The prevalence of white fingers recorded from these non manual workers was similar to that observed in other non vibration-exposed male Caucasian populations (typically from 6 to 10%)[49], hence qualifying them for this application. The motorcycle rider controls were general postal workers at large post offices, many of whom worked indoors. The suitability of such persons for a control group may again be challenged. However, the prevalence of white fingers in these persons was similar to that observed in other non vibration-exposed male Japanese populations (typically from 0.5 to 2.4%)[49]. It thus appears that the exposures in Table 5 fulfil the requirements for the absence of VWF.

For both the pavement breaker and motorcycle populations, the observed raw prevalence of white fingers was statistically indistinguishable from that of the respective control group. The lack of statistical significance for the operators of pavement beakers even though a difference in raw prevalence from controls of 0.1% was observed, which increased to 2.7% when adjusted for the age difference between exposed workers and controls[21], suggests the exposed population was bifurcated. The presumed deviation from a normal distribution could well indicate the presence of "low" and "high" exposure subgroups. In addition, both the pavement breaker and motorcycle populations contain persons with longer daily exposure times who are either known or presumed to have developed VWF, suggesting that the "low" exposure subgroups employed in the analysis represent exposures closer to the threshold for the onset of VWF. In these circumstances the assumption that $t(2)_{LI} / t(1)_{LI} \rightarrow 1$ may be considered to be valid.

There have been studies published elsewhere that have found frequency unweighted acceleration (from 6.3 to 1250 Hz) to be a better predictor of the development of VWF than the ISO frequency weighting[30, 31]. While the Griffin *et al.* and Bovenzi studies focused on the lifetime exposure to vibration (i.e., the product of the daily exposure and the total number of years exposed to vibration), the analysis presented in this paper is focused on comparing pairs of epidemiologic studies with similar group mean latencies for VWF. In this way, the differences between the daily exposures experienced by the two population groups become the metric for the evaluation of the risk for developing VWF. The consequences of employing frequency unweighted acceleration from 6.3 to 1250 Hz in the analysis described here can be seen by comparing the daily exposures for the different power tools and machine listed in columns 3 and 5 of Tables 3 and 6. Reference to the first row of these Tables provides values for unweighted accelerations from 6.3 to 1250 Hz. It is evident that the use of this "frequency weighting" results in the rock drill exposure being assessed as being much more harmful that the chain saw exposure (Table 3). Similarly, the pavement breaker exposure is assessed as much more harmful than the motorcycle exposure (Table 6). In each case, however, the epidemiologic data from almost 10,000 vibration-exposed workers indicates otherwise. Only by restricting the frequency range substantially to those shown in Fig. 5 can the estimates of the risk of VWF from measures of daily vibration exposure be reconciled with the health data.

Thus, by employing a defined end point for the health effect and comparing pairs of population groups, the detailed characteristics of the frequency content of the vibration exposure can be evaluated. The approach is strengthened if populations using tools and machines with effectively two modes of operation − "on" and "off" − can be identified. Unfortunately this is uncommon in the real world: in all our field studies, only some pneumatically powered tools, such as rock drills, have operated as essentially binary vibration sources. When day-long exposures to, for example, chain saw vibration are monitored, the periods of time during which the operator moves between tasks (e.g., with engine idling) result in discrepancies in the definition of "operating time" and influence the magnitude of the daily exposure[57, 58]. The coupling of vibration into the hand may also be expected to influence the exposure. Differences between day-long exposures recorded at the interface between the vibrating handle and the hand during a working day and the vibration recorded at the handle during "work simulations" are believed to constitute the largest uncertainty in the analysis described here[57, 58].

The frequency weighting for the onset of VWF derived from this analysis is based on the experiences of 9,934 vibration-exposed workers, and is remarkably similar to those derived by other methods (shown in Fig. 5). The upper frequency limit of the frequency weighting is almost indistinguishable from those of W_{hf} and W_{hT}. Frequency weightings W_{hf} and W_{hT} differ somewhat, however, at low frequencies from that derived here, which suggests values between them. There is agreement for a frequency weighting for the development of VWF that is frequency independent from about 25 Hz to 500 Hz (–3 dB frequencies). This range is broadly compatible with the results of studies of vasoconstriction in persons with VWF by Pyykkö and co-workers, summarized earlier, which served to inform the form of the primary frequency range for this analysis (i.e., as frequency independent) but not its extent (i.e., the lower and upper cut-off frequencies).

Alternate approaches to evaluating the suitability of different frequency weightings for predicting the development of VWF from epidemiologic data have recently been explored by Bovenzi, Pitts, and co-workers[9, 10]. They both considered the application of four frequency weightings to the acceleration spectra: ISO frequency weighting, unweighted acceleration from 6.3 to 1250 Hz, W_{hf} and W_{hT}. Additional frequency weightings were also considered by Pitts *et al.*, but their analysis did not identify a unique frequency weighting for the development of VWF. Of the frequency weightings considered by Bovenzi *et al.*, frequency unweighted acceleration (from 6.3 to 1250 Hz) provided the best fit to their data, followed by W_{hf} and W_{hT}. The conclusion was based on health data from eleven workers with VWF, and is not in agreement with the results of this analysis for the reasons discussed. Both analyses involved sophisticated statistical methods to deduce relationships that were statistically significant.

In summary, when considered together, the derivation of similar frequency weightings for the onset on VWF by completely different methods provides further evidence that the ISO frequency weighting may not be generally applicable for assessing the risk of developing VWF. A frequency weighting embodying the characteristics of those in Fig. 5 may provide improved assessment of VWF risk. The analysis described here does not consider other components of the hand-arm vibration syndrome.

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