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Original Article

Epidemiological Evidence for New Frequency Weightings of Hand-Transmitted Vibration

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Abstract: This paper provides an overview of the exposure-response relationship for the vascular component of the hand-arm vibration syndrome, called vibration-induced white finger (VWF). Over the past two decades, several epidemiological studies have shown a poor agreement between the risk for VWF observed in various occupational groups and that predicted by models included in annexes to International Standard ISO 5349 (ISO 5349:1986, ISO 5349-1:2001). Either overestimation or underestimation of the occurrence of VWF have been reported by investigators. It has been argued that the current ISO frequency-weighting curve for hand-transmitted vibration, which assumes that vibration-induced adverse health effects are inversely related to the frequency of vibration between 16 and 1250 Hz, may be unsuitable for the assessment of VWF. To investigate this issue, a prospective cohort study was carried out to explore the performance of four alternative frequency weightings for hand-transmitted vibration to predict the incidence of VWF in groups of forestry and stone workers. The findings of this study suggested that measures of vibration exposure which give relatively more weight to intermediate and high frequency vibration produced better predictions of the incidence of VWF than that obtained with the frequency weighting currently recommended in International Standard ISO 5349-1:2001.

Key words: Cohort study, Exposure-response relationship, Frequency weightings, Hand-transmitted vibration, ISO standards, Vibration-induced white finger

Introduction

Vibration-induced white finger (VWF) is a secondary form of Raynaud's phenomenon caused by occupational exposures to hand-transmitted vibration produced by hand-held power tools or industrial processes[1]. Since the attack of finger blanching is usually triggered by exposure to cold climate, the occurrence of VWF is more frequent in vibration exposed persons who work in the Nordic countries of Europe, Asia and America than in those living in equatorial or tropical areas[2].

Epidemiological studies have reported that the occurrence of VWF among vibration exposed workers has decreased in the last decades because of the introduction of tools equipped with antivibration devices, the reduction of daily exposure time, and the overall amelioration of work organisation[1, 2].

The quantitative relation between daily or lifetime exposure to hand-transmitted vibration and the development of VWF is not yet fully understood[2]. Annexes to international standards ISO 5349 (ISO 5349:1986[3], ISO 5349-1:2001[4]) have proposed tentative exposure-response relationships for vibration-induced disorders, but the findings of several epidemiological studies have shown a poor agreement between the risk for VWF observed in various occupational groups and that predicted by the ISO standards[2]. In the ISO exposure-response guidance the response is represented by VWF outcomes in terms of either latency time for the onset of finger blanching[3] or

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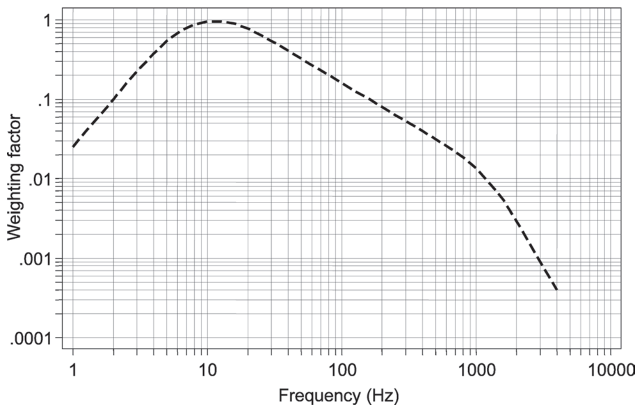

Fig. 1. Frequency weighting curve W_h for hand-transmitted vibration in International Standard ISO 5349-1:2001[4].

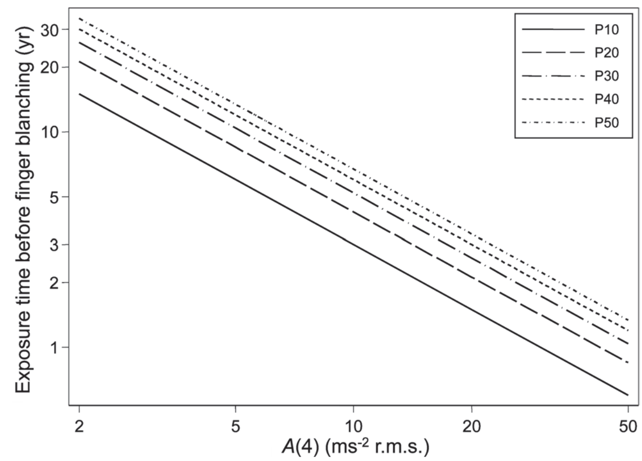

Fig. 2. Exposure-response relationship for vibration-induced white finger in ISO 5349:1986[3], expressed as the duration of exposure necessary before the onset of finger blanching (yr) in selected percentiles (P) of an exposed population as a function of frequency-weighted acceleration magnitude normalised to a period of 4 h ($A(4)$ in ms^{-2} r.m.s.).

prevalence of VWF[4], and the exposure is given by measures of daily "energy equivalent" acceleration magnitude frequency weighted according to a weighting function which is assumed to reflect the relative importance of different vibration frequencies to cause adverse health effects in the hand and arm.

The aims of this paper are to provide:

(i) a brief summary of the biodynamic, physiological and epidemiological background underlying the form of the dose-response relationship offered by international standards ISO 5349 (ISO 5349:1986[3], ISO 5349-1:2001[4]);

(ii) an overview of the epidemiological studies published from 1986 to 2010, in which the observed occurrence of VWF was compared with that predicted by the ISO models;

(iii) a report of the main findings of a prospective cohort study of VWF, conducted within the EU research project VIBRISKS, which investigated the performance of alternative frequency weightings for hand-transmitted vibration to predict the incidence of VWF in groups of vibration exposed workers[5].

The ISO Exposure-response Relationships for VWF

International Standard ISO 5349:1986[3] provided a frequency weighting for the measurement of the root-mean-square (r.m.s.) acceleration magnitude of tool vibration. The ISO weighting curve has slopes of 0 dB below 16 Hz and −6 dB per octave from 16 to 1250 Hz. The main features of this frequency weighting have been retained in the revised version of the standard, ISO 5349-1:2001[4], in which the characteristics of the band-limiting and weighting filters for the current frequency weighting (called W_h) are defined mathematically in an annex to the standard (Fig. 1). Basically, the ISO W_h weighting is derived from extrapolation of the findings of a laboratory study of subjective equal sensation of vibration greatness levels as a function of vibration frequency (3 to 300 Hz) applied to the hands of ten healthy subjects[6]. As aforementioned, the shape of the ISO weighting curve assumes that the sensitivity of the finger-hand-arm system to vibration is approximately proportional to vibration acceleration below 16 Hz, and decreases in inverse proportion to frequency from 16 to 1250 Hz. Thus, the ISO frequency weighting assumes that low frequency acceleration has more importance than intermediate and high frequency acceleration for predicting vibration-induced adverse health effects.

Annex A to ISO 5349:1986[3] proposed an exposure-response relationship for VWF in which the duration of exposure before finger blanching (i.e. latency time) is expressed as a function of r.m.s. weighted acceleration normalised to a period of 4 h ($A(4)$), for selected percentiles of an exposed population (from 10 to 50%), (Fig. 2). It is reported that this dose-response relation was derived from approximately 40 studies of vibration exposed worker groups with the following characteristics: (i) the exposed workers included persons in normal health who worked all day with only one type of tool or on an industrial process; (ii) the lifetime duration of exposure did not exceed

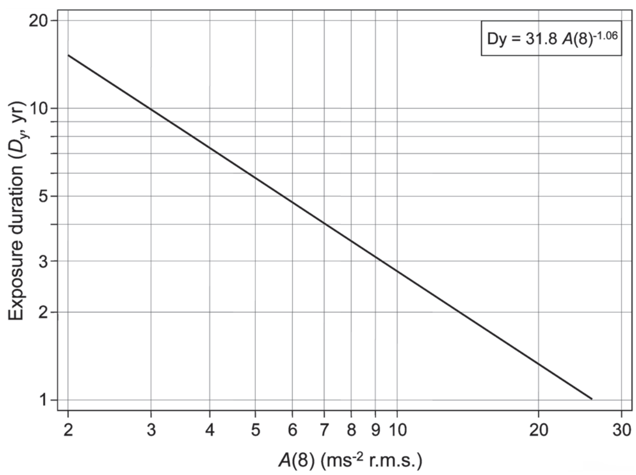

Fig. 3. Exposure-response relationship for vibration-induced white finger in ISO 5349-1:2001[4], expressed as the daily vibration exposure (8-h energy-equivalent frequency-weighted acceleration magnitude, *A*(8) in ms^{-2} r.m.s.) and the group mean lifetime exposure duration (yr), which are estimated to cause finger blanching in 10% of a vibration exposed population.

25 years; (iii) the frequency-weighted, dominant, single axis acceleration component of vibration of the tools was not in excess of 50 ms^{-2} r.m.s..

In International Standard ISO 5349-1:2001[4], a revision of the dose-response relationship for VWF was proposed, although it was said to be broadly compatible with that suggested in the previous version of the standard[7]. In Annex C to the revised standard, the dose-response relationship is restricted to a VWF prevalence of 10% predicted on the basis of the group mean lifetime exposure duration (years) and the daily vibration exposure expressed in terms of 8-h energy-equivalent frequency-weighted vibration total value ($A(8)$ in ms^{-2} r.m.s.), (Fig. 3). $A(8)$ is calculated from the daily exposure time and the root-sum-of-squares of the triaxial frequency-weighted r.m.s. components of vibration according to a second power time dependency (i.e., a^2t = constant). The current ISO guidance for VWF is said to derive from epidemiological studies of groups of workers who were exposed to hand-transmitted vibration up to 25 years and operated one type of power tool with vibration frequency above the range 30 to 50 Hz and with vibration magnitudes up to 30 ms^{-2} r.m.s..

Epidemiological Studies of the Exposure-response Relationship for VWF (1986 − 2010)

Table 1 reports the findings of epidemiological studies in which the observed VWF outcomes (latency time for the onset of finger blanching, prevalence or incidence of VWF) were compared with those predicted by the ISO models. The studies were retrieved from the databases MEDLINE, EMBASE, NIOSHTIC-2, CISDOC, and Google Scholar, the Proceedings of the International Conferences on Hand-Arm Vibration, and the Human Response to Vibration Literature Collection at the Institute of Sound and Vibration Research of the University of Southampton (UK). The literature search was limited to epidemiological studies published after the standard ISO 5349:1986[3] was officially adopted (1986 − 2010).

The search provided 21 studies of exposure-response relationship for VWF in about 35 occupational groups, and the findings were published in 25 papers[8–32]. Seventeen studies were of cross-sectional type[8, 9, 11,13–15,17–23, 25, 26, 28, 29] and four had both cross-sectional and longitudinal design[12, 27, 30, 31]. Most of the studies reported disagreement with the occurrence of VWF predicted by the ISO models. Overestimation of VWF risk was found in eleven studies (52.4%), mainly in worker groups exposed to high magnitudes of low frequency vibration from percussive tools such as rock drills, road breakers, stone hammers, and sand rammers[9, 11, 13, 14,18–21, 23, 25, 26]. Seven studies reported underestimation of the risk for VWF (33.3%) in workers who operated tools producing vibration with high frequency components (riveting tools, grinders)[8, 12, 15, 18, 20, 27, 30]. Good agreement with the ISO prediction was found in three studies of forestry workers[20], snowmobile drivers[22], and stone workers using rotary tools solely[25] (14.3%). It is worth noting that studies of forestry workers, the most frequently investigated occupational group, reported both disagreement (over or underestimation) and agreement with the ISO prediction for VWF[12,19–21, 26, 31]. The large heterogeneity of the findings arising from investigations of VWF may point at clinical, methodological or statistical issues. For instance, the influence of potential confounders, such as age, smoking habit, outdoor climate, type of tool, and work organisation, might not have been taken into account appropriately in the epidemiological studies of VWF occurrence.

To explain the discrepancy between the observed and expected VWF outcomes in epidemiological studies, the majority of authors argued that the ISO frequency weighting tends to give an excessive weight to low frequency vibration and to underestimate the importance of the intermediate and high frequency components of vibration. This view is supported by the findings of biodynamic investigations[33, 34] and physiological studies of the acute effects of vibration on finger circulation[35], as well as by

Table 1. Comparison between observed VWF outcomes (prevalence, incidence, or latency time for the onset of finger blanching) in epidemiological studies of vibration exposed worker groups (1986–2010), and expected VWF outcomes according to International Standards ISO 5349 (ISO 5349:1986[3]; ISO 5349-1:2011[4]). VWF is vibration-induced white finger, and AV is antivibration

Author(s) (year) [reference]	Worker group(s)	Tools	Observed VWF outcome (prevalence, incidence or latency)	Expected VWF outcomes (ISO 5349:1986; ISO 5349-1:2001)
Engström & Dandanell (1986) [ref. 8]	Aircraft industry workers	Riveting tools, drills, bucking bars	Prevalence 20.5% after 25 yr of exposure	Underestimation by a factor of four
Tasker (1986) [ref. 9]	Gas distribution workers	Road breakers	Prevalence 9.6% [ref. 10]	Overestimation
Brubaker *et al.* (1986) [ref. 11]	Miners	Jack-leg rock drills, stoper drills	Prevalence 45% Latency (median) 7.5 yr	Overestimation
Brubaker *et al.* (1987) [ref. 12]	Fallers	Large AV and non-AV chain saws	Prevalence 50.9% Latency (mean) 4.2 yr in AV chainsawyers, Incidence 30% (follow up 5 yr)	Underestimation
Bovenzi *et al.* (1988) [ref. 13]	Travertine workers	Rock drills, chipping hammers, vertical grinders, cutters	Prevalence 35.5%, Latency (median) 10 yr	Overestimation
Pelmear *et al.* (1989) [ref. 14]	Miners	Pneumatic hammers, pneumatic chipping chisels	Prevalence 43%, Latency (mean) 4 yr for the 9th percentile of VWF workers [ref. 24]	Overestimation by a factor of four
Nilsson *et al.* (1989) [ref. 15]	Platers	Grinders, die grinders, hammers	Prevalence 42% Latency (mean) 9.8 yr, 4 yr for the 10th percentile of VWF workers	Underestimation
Nelson & Griffin (1989, 1992) [ref. 16, 17]	Dockyards (caulkers, painters, boilermakers, smiths, combined trades)	Grinders, chipping hammers, drilling machines, nobblers, sanders, scaling tools	Prevalence 7% (smiths) to 81% (caulkers), Latency 5 yr (combined trades) to 28 yr (smiths) for the 20th percentile of VWF workers	Models with unweighted acceleration fitted VWF symptoms better than models with ISO frequency-weighted acceleration
Xu *et al.* (1990) [ref. 18]	Miners, metal workers, mechanic operators, grinders	Rock drills, breakers, grinders, pedestal grinding, chipping hammers, riveting tools, sand rammers	Prevalence 2.3% (grinders in steel factory) to 82.7% (grinders in tool manufactory), Latency (mean) 3.9 yr (tool manufactory) to 10.8 yr (copper miners)	- Overestimation for rock drillers and rammer operators; - Underestimation for pedestal grinding
Bovenzi *et al.* (1990) [ref. 19]	Forestry workers	Chain saws	Prevalence 29.2% Latency (mean) 9.4 yr	Slight overestimation
Starck *et al.* (1990) [ref. 20]	Forestry workers, foundry workers, shipyard workers, stone workers	Chain saws, pedestal grinding, pneumatic hammers, scaling hammers	- Forestry workers: Prevalence <7–40%, Latency <5 to >10 yr - Pedestal grinders: Prevalence 100%, Latency <1 yr - Shipyard workers: Prevalence 5%, Latency 16 yr - Stone workers: Prevalence 50–75%, Latency 6–9 yr	- Good agreement for forestry workers; - Underestimation for pedestal grinders; - Overestimation for shipyard and stone workers
Mirbod *et al.* (1992) [ref. 21]	Dental technicians, aircraft industry workers, sewing machine operators, digging laborers, forestry workers	Model trimmers, drills, sanders, grinders, polishers, vibrators, AV chain saws	Prevalence 2.2% (sewing machine operators) to 9.6% (forestry workers), Latency (mean) 14.2 yr for forestry workers	Overestimation by a factor of two for forestry workers
Anttonen & Virokannas (1992) [ref. 22]	Snowmobile drivers, reindeer herders	Snowmobile handlebars, chain saws	Prevalence 14% (snowmobile drivers) to 19% (reindeer herders)	Good agreement for snowmobile drivers and reindeer herders

Table 1. (Continued)

Author(s) (year) [reference]	Worker group(s)	Tools	Observed VWF outcome (prevalence, incidence or latency)	Expected VWF outcomes (ISO 5349:1986; ISO 5349-1:2001)
Keith & Brammer (1994) [ref. 23]	Miners	Jack-leg rock drills	Prevalence 43%, Latency (mean) 9.5 yr [ref. 11, 24]	Overestimation by a factor of two
Bovenzi *et al.* (1994) [ref. 25]	Stone workers	Rock drills, stone hammers, angle grinders	- Stone workers operating rotary tools: Prevalence 13.8%, Latency (mean) 12.7 yr - Stone workers operating percussive tools: Prevalence 36.7–40.7%, Latency (mean) 16.5 yr	- Good agreement for stone workers operating rotary tools - Overestimation for stone workers operating percussive tools
Bovenzi *et al.* (1995) [ref. 26]	Forestry workers	AV and non-AV chain saws	Prevalence 23.4%, Latency (mean) 9.8 yr	Overestimation
Barregard *et al.* (2003) [ref. 27]	Car mechanics	Nut-runners, grinders, drills, chisel hammers	Prevalence 15%, Latency (mean) 15 yr, Incidence 19 per 1000 person-years (follow up 15 yr)	Underestimation
Griffin *et al.* (2003) [ref. 28]	Forestry workers, stone workers, dockyard workers	Chain saws, rock drills, stone hammers, grinders, chipping hammers, drills, nobblers, sanders, scaling tools	Prevalence 13.8% (stone grinders) to 54.3% (dockyard caulkers)	Measures of cumulative vibration dose calculated from unweighted acceleration gave better predictions of VWF than equivalent dose measures using ISO frequency-weighted acceleration
Tominaga (2005) [ref. 29]	Forestry workers, foundry workers, stone workers, metal workers, miners	Chain saws, chipping hammers, jack hammers, rock drills, sand rammers	Prevalence 0 (quarry workers) to 55.7% (miners)	A new weighting curve, giving more weight to high frequency vibration and less weight to low frequency vibration, fitted VWF disorders better than the ISO frequency weighting
Burström *et al.* (2006) [ref. 30]	Workers employed at a plant manufacturing paper and pulp-mill machinery components	Grinders, hammers, drills, saws, screw drivers	Prevalence 39%, Latency (mean) 12 yr, Incidence 25.6 per 1000 exposure yrs (follow up 10 yr)	Underestimation
Bovenzi (2009, 2010) [ref. 31, 32]	Forestry workers, stone workers	Bush saws, chain saws, stone hammers, grinders	- Forestry workers: Prevalence 14.0%, Incidence 4.3% (follow up 3 yr) - Stone workers: Prevalence 38.2%, Incidence 14.3% (follow up 3 yr)	Measures of vibration dose constructed from unweighted r.m.s. acceleration over the frequency range 6.3–1250 Hz performed better for the prediction of VWF than dose measures derived from r.m.s. acceleration frequency weighted according to the current standards

the results of recent epidemiological studies of the prevalence and incidence of VWF in worker groups exposed to hand-transmitted vibration from a great variety of hand-held powered tools[17, 28, 29, 31]. One cross-sectional study of forestry workers, foundry operators, stone workers, and miners in Japan found that a weighting curve giving more weight to high frequency vibration and less weight to low frequency vibration, fitted VWF disorders better than the ISO frequency weighting[29]. Three epidemiological studies of forestry, stone and dockyard workers conducted in UK and Italy reported that measures of vibration dose calculated from unweighted acceleration gave better predictions of VWF than equivalent dose measures using ISO frequency-weighted acceleration[17, 28, 31].

Other criticisms to the ISO exposure-response relationship for VWF concern possible inadequacies of the assumptions underlying the predictive model and uncertainties about the appropriateness of the "energy equivalence" concept to evaluate vibration exposure over the work day[36, 37], but these issues are beyond the scope of this paper.

Alternative Frequency Weightings for hand-transmitted Vibration: the VIBRISKS Cohort Study

In addition to the frequency weighting method provided by ISO 5349-1:2001[4], a set of candidate frequency weightings for the evaluation of workplace vibration exposures is currently under consideration at the *Hand-transmitted vibration* Working Group 3 of the ISO technical committee ISO/TC 108/SC 4 *Human exposure to mechanical vibration and shock*[38]. These candidate frequency weightings are based on the findings of either epidemiological studies of vibration-exposed workers or biodynamic investigations of vibration power absorption in the fingers[29, 34].

This paper reports a summary of the findings of a longitudinal study[5] aimed at investigating the performance of four alternative frequency weightings to predict the incidence of VWF in a cohort of forestry and stone workers recruited in a four-year research project supported by the European Union (EU) and entitled "*Risks of Occupational Vibration Injuries* (VIBRISKS)".

VIBRISKS is a research project funded by the European Commission which seeks to improve understanding of the risk of injury from occupational exposures to mechanical vibration by means of epidemiological studies supported by fundamental laboratory research[39].

The VIBRISKS project included a Work Package (WP2) devoted to epidemiological studies of upper limb disorders (vascular, neurological, musculoskeletal) caused by hand-transmitted vibration. Investigators of three countries were involved in VIBRISKS WP2 (Italy, Sweden, United Kingdom). In Italy, the study population included 215 forestry operators working in seven public companies and 34 stone workers employed in one private company. The forestry workers used brush and chain saws equipped with anti-vibration devices, and the stone workers operated both rotary and percussive tools for marble processing.

Study population

For the purpose of this study, the cohort included 206 vibration-exposed workers (185 forestry operators and 21 stone workers) who were not affected with VWF symptoms at the initial survey conducted in October 2003 to February 2004. Of these workers, 146 subjects (70.9%) participated in three follow-up surveys, and 60 (29.1%) participated in either one or two follow-up investigations over the calendar period autumn 2004 to winter 2007. All subjects continued to work with vibratory tools during the follow-up period.

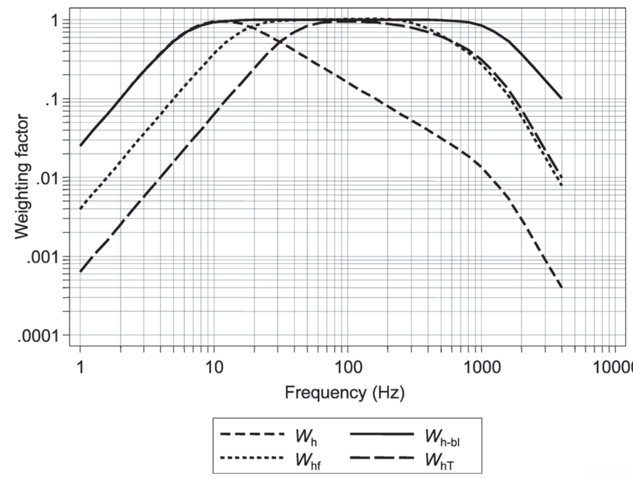

Fig. 4. Comparison of frequency weighting functions (W) for hand-transmitted vibration.
W_h: frequency weighting as defined in ISO 5349-1:2001[4], where h is hand; $W_{h\text{-}bl}$: the band-limiting component of W_h[4], where h is hand and bl is the band limit 6.3–1250 Hz; W_{hf}: a frequency weighting based on finger vibration power absorption[34, 38], where h is hand and f is finger; W_{hT}: a frequency weighting based on a Japanese study of VWF prevalence[29, 38], where h is hand and T is the initial of the author's family name (Tominaga).

A complete description of the cohort, the study design and the diagnostic methods for VWF (medical interview, administration of colour charts, and measurement of finger systolic blood pressure after a standardised cold test) have been reported in recent papers[31, 32, 40].

Frequency weightings and vibration exposure

Vibration generated by the tools used by the forestry and stone workers was measured in the field during real operating conditions. Vibration was measured in three orthogonal directions (x, y, z) according to the procedure recommended by international standard ISO 5349-1:2001[4].

Acceleration magnitudes were weighted using the frequency weightings (W) displayed in Fig. 4:

(i) W_h is the frequency weighting specified in ISO 5349-1:2001[4], where h is hand;
(ii) $W_{h\text{-}bl}$ is the band-limiting component of W_h[4], where h is hand and bl is the band limit 6.3 − 1250 Hz;
(iii) W_{hf} is a frequency weighting based on biodynamic studies of finger vibration power absorption[34], where

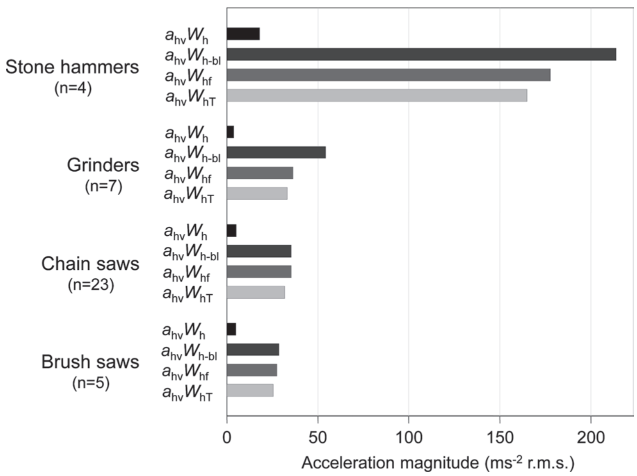

Fig. 5. Mean values of the root-sum-of-squares (vibration total value, a_{hv}) of the r.m.s. acceleration magnitudes generated by the vibratory tools of this study, weighted according to the four candidate frequency weightings (W_h, $W_{h\text{-}bl}$, W_{hf}, W_{hT}) displayed in Fig. 4.

h is hand and f is finger;

(iv) W_{hT} is a frequency weighting based on a Japanese study of VWF prevalence in worker groups investigated from 1957 to 1977[29], where h is hand and T is the initial of the author's family name (Tominaga).

Figure 5 reports the mean values of the root-sum-of-squares (vibration total value, a_{hv}) of the r.m.s. acceleration magnitudes generated by the vibratory tools of this study, frequency weighted according to W_h, $W_{h\text{-}bl}$, W_{hf}, or W_{hT}. As expected, the following rank order for the machine r.m.s. acceleration values was observed: $a_{hv}(W_{h\text{-}bl}) > a_{hv}(W_{hf}) > a_{hv}(W_{hT}) > a_{hv}(W_h)$, (Friedman's test for paired data: $p<0.001$).

Table 2 displays the rank correlation coefficients between the r.m.s. acceleration magnitudes weighted according to the four candidate frequency weightings. The correlations were strong for $a_{hv}(W_{h\text{-}bl})$ *vs* $a_{hv}(W_{hf})$ or $a_{hv}(W_{hT})$ (Kendall's tau 0.90 to 0.92), and very strong for $a_{hv}(W_{hf})$ *vs* $a_{hv}(W_{hT})$ (tau 0.98), while poorer rank correlation coefficients were obtained for $a_{hv}(W_h)$ *vs* r.m.s. accelerations weighted with the other alternative frequency weightings (tau 0.27 to 0.34).

To evaluate daily exposure duration to vibration, direct observation of exposure patterns at the workplace was made by supervisors over an entire week period. They used a stopwatch method and recorded the contact time the hands of the operators were actually exposed to the vibration from the tools.

Daily vibration exposure was evaluated according to international standard ISO 5349-1:2001[4] and expressed in terms of 8-h energy-equivalent frequency-weighted r.m.s. acceleration magnitude ($A(8)W_{hi}$):

Table 2. Kendall's rank correlation coefficients between r.m.s. acceleration magnitudes generated by the vibratory tools of this study (n=39). The r.m.s. acceleration magnitudes expressed as vibration total value (a_{hv}) are weighted according to the four candidate frequency weightings (W_h, $W_{h\text{-}bl}$, W_{hf}, W_{hT}) displayed in Fig. 4

Frequency weightings	$a_{hv}(W_h)$	$a_{hv}(W_{h\text{-}bl})$	$a_{hv}(W_{hf})$	$a_{hv}(W_{hT})$
$a_{hv}(W_h)$	1.0	–	–	–
$a_{hv}(W_{h\text{-}bl})$	0.273	1.0	–	–
$a_{hv}(W_{hf})$	0.337*	0.905**	1.0	–
$a_{hv}(W_{hT})$	0.320*	0.922**	0.983**	1.0

p-value (Bonferroni adjusted): *<0.05; **<0.001.

$$A(8)W_{hi} = \sqrt{\frac{1}{T_0}\sum_{i=1}^{n}(a_{hvi}(W_{hi}))^2 T_i} \qquad \left(ms^{-2} r.m.s.\right)$$

where $a_{hvi}(W_{hi})$ is the vibration total value (frequency weighted with W_h, $W_{h\text{-}bl}$, W_{hf}, or W_{hT}) for tool i in ms^{-2} r.m.s., T_i is the daily duration of exposure to tool i in hours, and T_0 is the reference duration of 8 h.

Longitudinal data analysis

The relations of VWF incidence (binary outcome) to alternative measures of vibration exposure were assessed in terms of odds ratios (OR) and robust 95% confidence intervals (95% CI) by means of the generalised estimating equations (GEE) method to account for the within-subject dependency of the observations over time. The significance of the associations was assessed with the Wald χ^2 test.

The "quasi-likelihood under the independence model criterion" (QIC), a modification of the Akaike's Information Criterion (AIC), was used to select the best working correlation structure in GEE analyses, and to compare the fit of GEE longitudinal models including alternative measures of daily vibration exposure[41, 42]. The model with the smallest QIC value was chosen as the best-fitting model for the relation between VWF and vibration exposure. To aid comparison, a ΔQIC was calculated as the difference between the QIC values for a specific exposure model and the model including $A(8)$ calculated with frequency weighting W_h (i.e. the ISO weighting method). Although fit statistics for GEE models are still under active research[43], guidelines for selecting the best-fitting model may be borrowed from strength of evidence rules developed for the AIC method[44]: a $\Delta QIC \leq 2$ suggests no difference in the fit between models, $4 \leq \Delta QIC \leq 7$ tends to give support for

Table 3. Odds ratios (OR) and robust 95% confidence intervals (95% CI), estimated by GEE-logistic modelling, for the association between the cumulative incidence of vibration-induced white finger and measures of vibration exposure expressed in terms of *A*(8) and years of follow up. *A*(8) was calculated by weighting the tool r.m.s. acceleration magnitudes according to the four candidate frequency weightings (W_h, $W_{h\text{-}bl}$, W_{hf}, W_{hT}) displayed in Fig. 4. The Wald χ^2 test for the measures of vibration exposure, and the quasi-likelihood under the independence model criterion for the comparison between models (QIC) are given

Predictors	OR (95% CI)	Wald χ^2 test	QIC	ΔQIC*
$A(8)W_h$ (ms^{-2} r.m.s)	1.19 (1.03–1.37)	5.62 (p=0.018)	1198	0**
Follow up time (yr)	2.07 (1.52–2.82)	21.6 (p<0.001)		
$A(8)W_{h\text{-}bl}$ (×10 ms^{-2} r.m.s)	1.15 (1.03–1.28)	5.71 (p=0.017)	1184	−14
Follow up time (yr)	2.05 (1.50–2.80)	20.5 (p<0.001)		
$A(8)W_{hf}$ (×10 ms^{-2} r.m.s)	1.17 (1.01–1.34)	4.58 (p=0.032)	1192	−6
Follow up time (yr)	2.05 (1.51–2.78)	21.1 (p<0.001)		
$A(8)W_{hT}$ (×10 ms^{-2} r.m.s)	1.18 (1.02– .38)	4.80 (p=0.029)	1190	−8
Follow up time (yr)	2.05 (1.51–2.78)	21.0 (p<0.001)		

*Guidelines for selecting the best-fitting model (**reference model): ΔQIC ≤ 2: no difference in the fit between models. 4 ≤ ΔQIC ≤ 7: the model with the smaller QIC provides a better fit to the data. ΔQIC > 10: the model with the smaller QIC provides a substantial better fit to the data.

Table 4. Observed and predicted cumulative incidence of vibration-induced white finger (VWF) in the vibration-exposed workers by job title and alternative measures of daily vibration exposure expressed as 8-h energy-equivalent acceleration magnitude (*A*(8)). *A*(8) was calculated by weighting the tool r.m.s. acceleration magnitudes according to the four candidate frequency weightings (W_h, $W_{h\text{-}bl}$, W_{hf}, W_{hT}) displayed in Fig. 4. The predicted incidence of VWF is estimated by the GEE method (see models in Table 3)

Job title	Observed VWF incidence (%)	Predicted VWF incidence (%)			
		$A(8)W_h$	$A(8)W_{h\text{-}bl}$	$A(8)W_{hf}$	$A(8)W_{hT}$
Forestry workers	4.3	5.4	5.0	5.1	5.1
Stone workers	14.3	8	12	11	11

the model with the smaller QIC, ΔQIC > 10 means that the model with the smaller QIC provides a substantial better fit to the data.

Frequency weightings and exposure-response relationship for vwf

At the cross-sectional study the cohort included 249 vibration exposed workers and the point prevalence of VWF was 17.3% (43/249). According to job title, VWF prevalence was 14.0% in the forestry workers (30/215), and 38.2% in the stone workers (13/34). Over the follow-up period, there were 11 new cases of VWF, giving a three-year incidence of 5.3% (11/206). The cumulative incidence of VWF was 4.3% in the forestry workers (8/185), and 14.3% in the stone workers (3/21).

Table 3 reports the relations between the incidence of VWF and vibration exposure over the follow-up period. In general, all alternative measures of daily vibration exposure were significantly associated with an increased risk for VWF over time. The excess risk for VWF varied from 15 to 19% per unit increase in daily vibration exposure (1 ms^{-2} for $A(8)W_h$, 10 ms^{-2} for $A(8)W_{h\text{-}bl}$, $A(8)W_{hf}$ or $A(8)W_{hT}$). Duration of exposure was also a significant predictor of VWF (OR 2.0 per year of follow-up). The magnitude of the QIC statistic and the ΔQIC values suggested that the model including $A(8)W_{h\text{-}bl}$ provided a better fit to VWF incidence than the other alternative measures of daily vibration exposure (ΔQIC 6 to 14). Moreover, the QIC statistic tended to give more support to models with $A(8)W_{hf}$ (ΔQIC 6) or $A(8)W_{hT}$ (ΔQIC 8) as predictors for VWF than that with $A(8)W_h$. The difference between $A(8)W_{hf}$ and $A(8)W_{hT}$ models was negligible (ΔQIC 2).

Table 4 compares the observed incidence of VWF in the vibration exposed workers with those predicted by the alternative measures of daily vibration exposure (based on the models in Table 3). There were minor discrepancies between the predictions of the various models (5%) and the observed VWF incidence in the forestry workers (4%). The $A(8)W_{\mathrm{h}}$ model tended to underestimate the incidence of VWF in the stone workers (8%), while the alternative models provided a better prediction of the outcome (observed incidence 14% *vs* predicted incidence 12% for $A(8)W_{\mathrm{h\text{-}bl}}$ and 11% for $A(8)W_{\mathrm{hf}}$ or $A(8)W_{\mathrm{hT}}$).

In previous longitudinal studies of the VIBRISKS research project, significant associations were found between VWF and some predictors such as age at entry, body mass index and smoking[31, 32]. However, the difference in the estimates of the odds ratio for $A(8)W_{\mathrm{hi}}$ between the models of this study and multivariable models including additional predictors was less than 10%. Therefore, in the present study simpler exposure-response relationships for VWF are shown to make them comparable with the predictive model recommended in annex C to ISO 5349-1:2001[4].

There are some potential sources of bias in this longitudinal study which have been discussed in detail elsewhere[5, 31, 32], such as the short duration of the follow up time, vibration measured with a r.m.s. averaging procedure, and uncertainties about the estimation of vibration exposure over time since vibration measurement was limited to the tools currently used by the forestry and stone workers.

Implications of findings for improving frequency weighting

In this prospective cohort study, the four candidate frequency weightings W_{h}, $W_{\mathrm{h\text{-}bl}}$, W_{hf}, and W_{h}T were used to construct alternative measures of daily vibration exposure expressed as $A(8)$ in accordance with ISO 5349-1:2001[4].

Data analysis with a GEE-logistic model showed that measures of vibration exposure which give more weight to intermediate and high frequency vibration fitted VWF disorders better than a measure derived from the ISO frequency weighting. Moreover, a measure of statistical fit gave more support to the model including $A(8)W_{\mathrm{h\text{-}bl}}$ rather than $A(8)W_{\mathrm{hf}}$ or $A(8)W_{\mathrm{hT}}$, even though the various GEE models gave rise to similar predictions of VWF. The high correlation between $a_{\mathrm{hv}}(W_{\mathrm{hf}})$ and $a_{\mathrm{hv}}(W_{\mathrm{hT}})$, and the output from data modelling suggest that the difference between W_{hf} and W_{hT} is too small for preferring one of these two frequency weightings. *It should be recognised, however, that selecting a model on the basis of a fit statistic does not always mean that the chosen model provides the most plausible interpretation of the occurrence of a health disorder.*

In this study, the discrepancy in the predictions of VWF between the ISO weighting and the other alternative frequency weightings was small for the forestry workers but more substantial for the stone workers. These findings may be explained, at least partially, taking into account the differences in the frequency components of vibration spectra produced by the vibratory tools. Frequency analysis of tool vibration showed that the highest unweighted r.m.s. acceleration magnitudes for the chain saws were detected between 100 and 200 Hz, while low acceleration values were measured outside this frequency range[5]. Conversely, the stone hammers produced high-magnitude shocks containing energy over a wide range of intermediate and high frequency vibration[5]. Since the ISO W_{h} curve greatly reduces the contribution of high frequency vibration to the magnitude of frequency weighted acceleration, these frequency components are likely to play an important role in the onset of VWF disorders.

The VIBRISKS study is the first one in which exposure-response relationship for VWF has been investigated by means of incidence data. The findings of this prospective cohort study tend to support those of biodynamic and physiological investigations suggesting that over the frequency range of vibration measurement required by the ISO standard (6.3 to 1250 Hz) more importance should be given to vibration frequencies ≥ 20 Hz[33–35]. In addition, the VIBRISKS incidence study strengthens the conclusions of previous cross-sectional surveys which showed that measures of daily or cumulative vibration dose derived from unweighted r.m.s. acceleration were better predictors of the occurrence of VWF than equivalent doses calculated from ISO weighted acceleration[17, 28].

The hand-arm vibration syndrome includes vascular, sensorineural and musculoskeletal disorders in the upper limbs[1, 2]. The findings of biodynamic, physiological and epidemiological studies have suggested that the frequency of vibration is a strong determinant for the pathogenic mechanisms underlying these disorders. In ISO 5349-1:2001[4] it is said that the frequency weighting W_{h} is used to assess **all biological effects** of hand-transmitted vibration, but it is unlikely that one frequency weighting may be appropriate to cover all adverse health effects associated with vibration exposure since the ISO frequency weighting relates to short-term, acute, sensory effects rather than to long-term, chronic, disorders, including VWF[2, 6, 37].

One argument for retaining the W_{h} curve is the large amount of vibration and health data collected so far with the current ISO weighting method. Other arguments are the possible implications that a change in W_{h} may have for employers who must manage the provisions of the

EU Directive on mechanical vibration, and for designers and manufactures of tools, work equipment, and personal protective equipment[45]. These arguments are reasonable and deserve attention, but the results of this and other cross-sectional and longitudinal studies suggest that there is sufficient epidemiological evidence for giving more weight to intermediate and high frequency vibration to evaluate the severity of hand-transmitted vibration, at least for the vascular component of the hand-arm vibration syndrome. These findings, in addition to those provided by biodynamic and physiological studies of the frequency-dependent effects of vibration, can lead to a better understanding of the exposure-response relationships for vibration-induced health disorders and can contribute to an improvement or change in the vibration frequency weighting currently recommended by the international standard ISO 5349-1:2001[4].

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