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Original Article

Relative Performance of Frequency Weighting W_h and Candidates for Alternative Frequency Weightings for Predicting the Occurrence of Hand-transmitted Vibration-induced Injuries

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Abstract: Exposure to hand-transmitted vibration is usually assessed according to International Standard ISO 5349-1:2001 using the frequency weighting W_h. This paper compares eight frequency weightings that might be used to supplement or replace W_h. The comparison is based on a data from two databases, one containing over 7200 measured hand-arm vibration (HAV) spectra from a wide range of industrial machines the other recording exposure history and injury for workers referred to the Health and Safety Laboratory. Acceleration spectra from the machinery database are analysed to give weighted values for the alternative frequency weightings. These weighted values are compared and then used to estimate a set of alternative lifetime vibration dose values for subjects in the referral database. Statistical comparison of these lifetime dose values against assessments of hand-arm vibration syndrome (HAVS) and sensorineural HAVS prevalence suggests that values based the two weightings W_h and W_{h50lp} (the W_h weighing low-pass filtered at 50 Hz) provide the strongest indicators for developing these injuries. For vascular HAVS there was no clear evidence to advocate any individual frequency weighting. For all injury categories the strongest relationships were for the first power of acceleration magnitude.

Key words: hand-transmitted vibration, HAV, HTV, Hand-arm vibration syndrome, HAVS, Frequency weighting, ISO 5349, W_h

Introduction

Exposure to hand-transmitted vibration is usually assessed according to International Standard ISO 5349-1:2001[1)]. The exposure evaluation method defined in ISO 5349-1:2001 is based on a vibration measurement using the frequency weighting W_h which accounts for the fact that different frequencies of vibration are considered to represent different vibration risks, with a higher weighting factor representing a higher relative risk. The weighting W_h is consolidated in ISO 8041:2005[2)] which provides the full specification for instrumentation for measuring human response to vibration.

Although ISO 5349-1:2001 and ISO 8041:2005 are relatively recent standards, W_h has actually been in use, in one form or another, since the mid 1970s. Consequently the weighting has been used in many research studies and is embedded in many standards, guidance documents and legislation relating to work-place hand-arm vibration exposure. However, various researchers have highlighted concerns about the suitability of the W_h weighting for predicting the likelihood of hand-transmitted vibration

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injury (e.g.[3–6]). There is some evidence that the risks from machines dominated by low-frequency vibration may be over-estimated by W_h, while the risks from higher-frequency machines may be under-estimated.

In September 2008, of a group of experts working on the hand-transmitted vibration aspects of human exposure to mechanical vibration and shock working group (ISO/TC 108/SC 4/WG3) agreed to consider frequency weightings in addition to the existing W_h frequency weighting. However, they recognised that evidence to support specific alternative weightings is limited and sought to encourage further research by promoting a set of three candidates for alternative weightings[7].

Lifetime vibration dose values based on the ISO/TC 108/SC 4 candidate frequency weightings along with other variants of the W_h weighting have been investigated in this study. These lifetime exposure values have been compared to the development of any form of HAVS and the sensorineural and vascular components of HAVS. The aim of the work being to identify those frequency weightings that are likely to be the most reliable when predicting health outcomes.

In this paper vibration magnitudes calculated using frequency-weighting W_x are expressed as a_x (*e.g.* a vibration value based on the $W_{h\text{-}bl}$ weighting is expressed as $a_{h\text{-}bl}$).

Subjects and Methods

Data sources

This study is based on a combination of data from two databases operated by the Health and Safety Laboratory (HSL); the HSL referrals database and the HSL HAV machine database.

Table 1. Numbers of acceleration data sets in each HSL questionnaire category

ID	Category Name	No. of data sets
1	Chipping hammers	207
2	Rock drills	1889
3	Large angle grinders	559
4	Small angle grinders	311
5	Road breakers	186
6	Disc cutters	98
7	Vibrating compaction plates	161
8	Rollers	–
9	Vibrating poker	–
10	Scabbler	–
11	Rammers	69
12	Needle Scaler	135
13	Sanders	328
14	Die Grinders	205
15	Saws	199
16	Planer	–
17	Impact Drills	1506
18	Wrenches	148
19	Riveting hammers	–
20	Nail guns	297
21	Nibblers	35
22	Floor polishers	–
23	Brush cutters	119
24	Chainsaws	654
25	Hedgecutters	7
26	Mowers	7
27	Scarifiers	–
28	Rotavators	–
29	Blowers	6
30	High pressure water hoses	31
31	Pedestal grinders	58
32	Bench saws	26
33	Linishers	4
34	Floor mounted nibblers	–

HAVS referrals database

Health outcome data from two study groups: referrals to HSL for physician-led diagnosis and staging of HAVS (n=318), and data from a questionnaire-led workplace study (n=63). Both studies used the same exposure questionnaire. The questionnaire identifies 34 machine categories (listed in Table 1) against which subjects are asked to estimate daily machine usage times and numbers of years of exposure.

Referrals to HSL are primarily for workers displaying HAVS symptoms, but also include a number where the referral assessment was their primary health surveillance in a workplace where vibrating tools were used. The criteria for inclusion to the study population for referrals was that the standardised exposure questionnaire had been completed and a formal diagnosis of HAVS or not had been agreed.

The workplace study included those working in the manufacture of basic metals, construction including road construction, motor vehicle repair and gardeners or groundsmen. The inclusion criteria for subjects for this study group were that they had completed the exposure questionnaire and that they had answered negatively to a key number of questions concerning whether they had been diagnosed with HAVS and whether they suffered from symptoms of finger blanching, tingling or numbness, not including while using vibrating tools.

The two study populations had similar age ranges and occupational exposure times. The mean (and standard deviation) age of the referrals group was 46.1 (9.0) years and that of the workplace study group was 41.6 (11.4) years. The mean (and standard deviation) durations of occupational exposure to vibration was 22.7 (10.4) years in the referrals group and 19.9 (12.4) in those from the worker study group.

Carpel tunnel syndrome (CTS) is associated with hand-arm vibration exposure, however, the study group could not be separately analysed for CTS. About a third of the study population had a 'presumptive diagnosis' of CTS (5% CTS alone, 27% CTS with HAVS). This 'presumptive diagnosis of CTS' is based on the medical history and clinical assessment, including the physicians' opinion of the nature of symptoms, their distribution, time of occurrence and successful alleviation strategies.

HAV machine database

The HAV machine database is a database of hand-transmitted vibration magnitude data from HSL's many years experience of measuring workplace exposures. The criteria for inclusion on this study is that the data includes 1/3rd octave vibration spectra from which frequency-weighted values can be computed and that the vibration spectra were measured in accordance with ISO 5349-1:2001[1]. All measurements are triaxial at the hand-position with the highest W_h vibration magnitude; and although some predate ISO 5349-1:2001, all measurements are all consistent with current measurement standards. Machine data were available in 25 machine of the 34 machine categories used in the HSL HAVS referrals database (i.e. vibration measurement data were not available for 9 machine categories). The machine categories are listed in Table 1 along with the number of data sets available in each category.

Frequency-weightings

The candidate frequency-weightings defined by the International Standards Organisation' s hand-arm vibration working group, ISO/TC 108/SC 4/WG 3 are:

$W_{h\text{-}bl}$: A frequency-weighting based on the band-limiting component of W_h

W_{hT}: A frequency-weighting based on epidemiological data of incidence of vascular injury[5]

W_{hf}: A frequency-weighting based on finger vibration power absorption

The weighting W_{hf} is based on an analysis reported by Dong in 2008[8] to ISO/TC 108/SC 4. This analysis was based on the frequency-dependency of the triaxial finger biodynamic response under several different excitations and finger forces. All three weightings are illustrated in

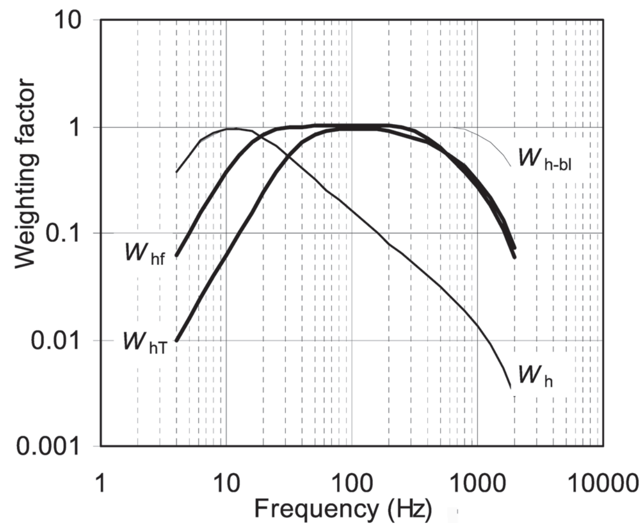

Fig. 1. Comparison of weightings W_h and $W_{h\text{-}bl}$, from ISO 8041 and weightings W_{hf} and W_{ht} proposed by ISO hand-arm vibration working group.

Fig. 1.

In addition to the candidate weightings defined by ISO/TC 108/SC 4/WG 3, five additional weightings have also been considered in this paper. Two are based on Annex E of VDI Guideline VDI 2057 Part 2[9]. This VDI Guideline divides the frequency range of the W_h filter into components above and below 50 Hz:

$W_{h50\text{-}lp}$: The W_h weighting with an additional 24dB/octave low-pass filter at 50 Hz

$W_{h50\text{-}hp}$: The W_h weighting with an additional 24dB/octave high-pass filter at 50 Hz

The vibration magnitudes given by these two subdivisions of W_h, when expressed as percentages of the vibration magnitude given by the full W_h weighting (a_h), are used in the VDI Guideline to indicate increased risks of either:

Bone and joint diseases (where $a_{h50\text{-}lp}$ is more than 75% of a_h) or

Neurosensory and vascular disturbances (where $a_{h50\text{-}hp}$ is more than 75% of a_h).

In this paper the VDI 2057 division of the W_h weighting into two parts is treated as two separate additional frequency weightings shown in Fig. 2.

The final three weightings considered are.

· W_{h100lp}: The W_h weighting, with an additional 24dB/octave low-pass filter at 100 Hz

· W_{h200lp}: The W_h weighting, with an additional 24dB/octave low-pass filter at 200 Hz

· W_{h500lp}: The W_h weighting, with an additional 24dB/octave low-pass filter at 500 Hz

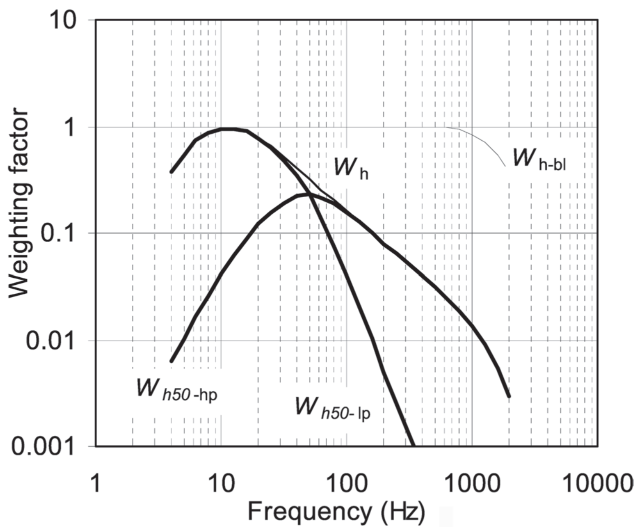

Fig. 2. Comparison of weightings W_h and $W_{h\text{-}bl}$, from ISO 8041 and weightings $W_{hVDI\text{-}lp}$ and $W_{hVDI\text{-}hp}$ based on VDI 2057:2002 part 2.

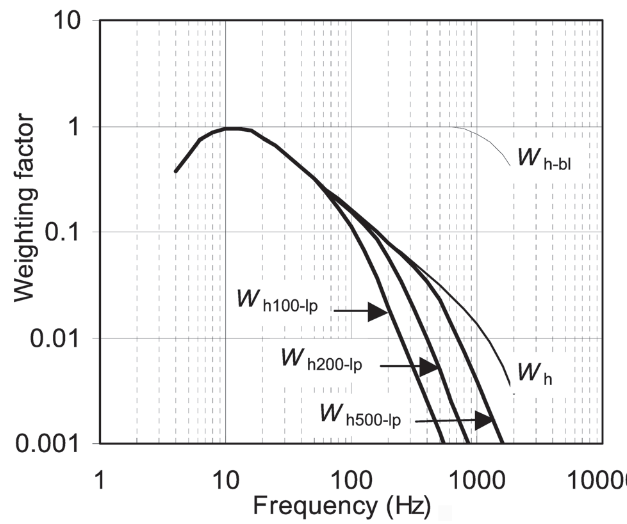

Fig. 3. Comparison of weightings W_h and $W_{h\text{-}bl}$, from ISO 8041 and weightings $W_{h100\text{-}lp}$, $W_{h200\text{-}lp}$ and $W_{h500\text{-}lp}$.

These weightings (illustrated in Fig. 3) were included to investigate the practical difference made by including frequencies beyond 200 and 500 Hz. At these higher frequencies the complexity (and hence cost) of measurement increases. Therefore there are practical benefits if adequate measurement is possible over reduced frequency ranges.

Vibration magnitude assessments

The HSL database of hand-arm vibration measurements contains the results from over 7200 individual field measurements of hand-transmitted vibration on over 800 machines in 25 machine categories.

For this investigation, the vibration spectra in the HSL machine database were used to calculate frequency-weighted vibration magnitudes using W_h plus the eight candidate alternative frequency weightings. Where data were available for two hand positions, only the hand position with the highest a_h value (frequency-weighted magnitude using weighting W_h) was used.

Frequency-weighted vibration magnitudes for all nine frequency weightings have been assessed both for individual results and group average data when grouped by machine category.

Lifetime vibration dose assessments

The risk from vibration injury is normally assumed to be proportional to the lifetime vibration dose[4)], however, there is no standardised method for evaluating lifetime dose values. In this paper we assume that the lifetime dose from one machine is a product of a power of the frequency-weighted vibration magnitude and total lifetime exposure time. The total lifetime vibration dose is then the sum of lifetime doses from all machines used by an individual, and can be expressed by equation 1:

$$dose = \Sigma a_{xi}{}^{m} t_i \qquad (1)$$

Where, for machine category i, t_i is lifetime exposure duration and a_{xi} is the acceleration magnitude evaluated using frequency weighting x. In this paper the power m is given the value 0, 1, 2 or 4.

Data from the HAVS referrals database along with frequency-weighted vibration magnitude values derived from the HSL machinery database, allowed lifetime vibration dose values to be calculated using Equation 1 and the alternative frequency weightings.

Of the total referral population, sufficient data were available to estimate lifetime vibration doses on 381 subjects. The analyses looked for correlations between lifetime exposures (up to time of first symptoms) and three hand-arm vibration injury groups those with:

- Any form of HAVS
  224 out of 381 (59%) with HAVS
- Vascular HAVS
  131 out of 381 (34%) with vascular HAVS
- Sensorineural HAVS
  217 out of 381 (57%) with sensorineural HAVS

Statistical analyses

Simple regression analysis was performed on the vibration magnitude data to assess whether the nine frequency

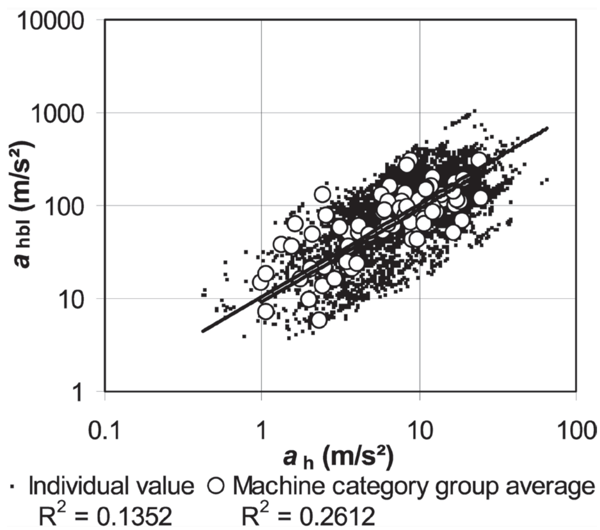

Fig. 4. Comparisons of weightings showing weak correlation between $a_{h\text{-}bl}$ and a_h.

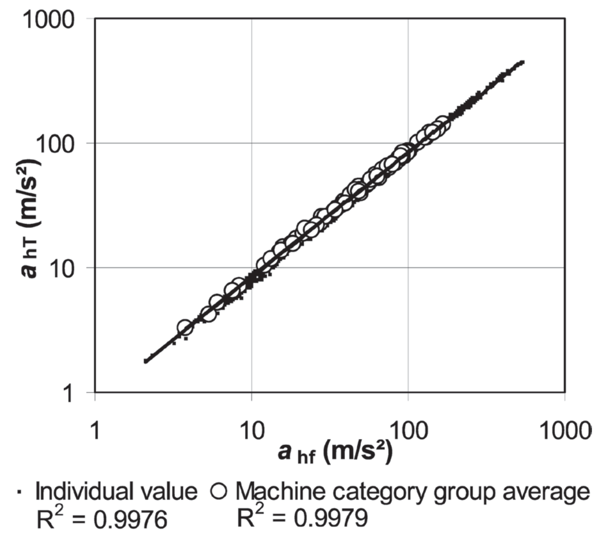

Fig. 5. Comparisons of weightings showing strong correlations between a_{hf} and a_{hT}.

weightings are usefully different from one another. The regression used the Microsoft Excel graph *Trendline* function with the line constrained to go through the origin to provide coefficient of determination values R^2.

More detailed statistical analyses were carried out to investigate the relative strengths of the alternative lifetime vibration dose models provided by Equation 1 and the alternative frequency weightings. A method used by Griffin *et al.*[4)] of dividing lifetime exposures into quintiles has been used to investigate the strength of the relationship between lifetime exposures and prevalence of HAVS. The analyses used for exposure duration either the exposure duration to the date of the questionnaire (for those without HAVS) or, duration at the date of first onset of symptoms (for those with HAVS). The statistical analyses were adjusted to account for age as a confounding factor. In these analyses, the expectation is that a good dose model will show increasing dose values with increasing quintile. To compare the strength of fit of the quintile data from the alternative dose models, the Bayesian Information Criterion (BIC)[11)], has been used. Lower BIC values suggest stronger fit; differences between BIC values of less than two suggest weak evidence for favouring one relationship above another; differences greater than 10 suggest very strong evidence.

Results

Evaluation of frequency-weighted magnitudes

The vibration magnitude values calculated with all the alternative frequency weightings were compared against one another. Two examples, representing the extreme situations are illustrated in Fig. 4 and Fig. 5 for individual data (dots) and data grouped by machine category (circles). The coefficients of determination, R^2, for Fig. 4 are low; for Fig. 5, the R^2 values are very close to 1. The R^2 values of Fig. 5 show that a_{hf} and a_{hT} are very closely related. Weighting pairs such as W_h and W_{h100lp} also have R^2 values close to 1. The relationships between such weightings are probably too close for them to be considered separately in further analysis. Conversely, Fig. 4 shows that a_h and $a_{h\text{-}bl}$ are very different and $W_{h\text{-}bl}$ is therefore a useful candidate weighting, in that it would give a dose-response relationship that is quite different to W_h.

Fig. 6 shows the outcomes of regression analyses on pairings of all nine frequency weightings. The R^2 values from these analyses highlight that some weighting pairs are not very different, and are unlikely to provide significantly different relative analyses of exposure. The regression analyses have been used to reduce the nine alternative weightings to a representative set of 5:

W_h (representing W_h, W_{h500lp}, W_{h200lp} and W_{h100lp})
W_{hbl}
W_{hf} (representing W_{hf} and W_{hT})
W_{h50lp}
W_{h50hp}

Lifetime vibration dose analyses

The vibration doses of the referral subjects have been divided into quintiles and the prevalence of injury in each

R^2 - based on individual data values

	$a_{h\text{-}bl}$	a_{hf}	a_{hT}	$a_{h50\text{-}hp}$	$a_{h50\text{-}lp}$	a_{h100lp}	$a_{hw200lp}$	$a_{hw500lp}$
a_h	0.26	0.33	0.32	0.68	0.80	0.91	0.97	1.00
$a_{h\text{-}bl}$		0.85	0.85	0.42	0.01	0.03	0.05	0.14
a_{hf}			1.00	0.74	0.03	0.20	0.20	0.32
a_{hT}				0.75	0.02	0.10	0.20	0.31
$a_{h50\text{-}hp}$					0.31	0.48	0.62	0.70
$a_{h50\text{-}lp}$						0.94	0.82	0.72
a_{h100lp}							0.94	0.98
$a_{hw200lp}$								0.98

R^2 - based on machine-category group average data values

	$a_{h\text{-}bl}$	a_{hf}	a_{hT}	$a_{h50\text{-}hp}$	$a_{h50\text{-}lp}$	a_{h100lp}	$a_{hw200lp}$	$a_{hw500lp}$
a_h	0.14	0.32	0.32	0.77	0.71	0.88	0.96	0.99
$a_{h\text{-}bl}$		0.80	0.81	0.21	-0.31	-0.27	-0.27	-0.19
a_{hf}			1.00	0.65	-0.17	-0.02	0.08	0.20
a_{hT}				0.66	-0.18	-0.03	0.08	0.20
$a_{h50\text{-}hp}$					0.22	0.51	0.66	0.74
$a_{h50\text{-}lp}$						0.89	0.74	0.62
a_{h100lp}							0.96	0.89
$a_{hw200lp}$								0.98

Key:	R^2 range:		
< 0.4	0.4 - 0.8	0.8 - 0.98	0.98 - 1

Note - R^2 values are calculated using the *Microsoft Excel* LINEST function, with the trend-line forced through the origin - this method has produced some negative R^2 values

Fig. 6. Regression analyses, R^2 values based on individual data and machine-category group average data.

quintile determined. Fig. 7 shows the resultant relationships for prevalence for any form of HAVS. Fig. 8 shows the relationships for prevalence for the sensorineural component of HAVS and Fig. 9 the relationships for prevalence for the vascular component of HAVS. It is clear from these three figures that the BIC values indicate that the best relationships are based on the first power of weighted acceleration magnitudes or, for vascular HAVS, exposure time alone.

For HAVS and sensorineural HAVS the results shown in Fig. 7 and Fig. 8 are quite similar, this is probably due to the large overlap in the two populations. The strongest relationships according to the BIC values are shown for two weightings W_h and W_{h50lp}. Visual inspection of the quintile data can appear to support other relationships (e.g. $a^4_{hf}\, t$ in Fig. 7), however, these are not supported by the BIC values.

For vascular injury the quintile relationships shown in Fig. 9 appear generally weak and the BIC is unable to discriminate strongly between the first power dose measures or dose based on exposure time alone.

Discussion

Frequency-weighted magnitudes

This investigation of the candidate alternative frequency weightings for hand-transmitted vibration exposure evaluation has considered whether the frequency weightings have the potential to provide useful alternative assessment methods. Fig. 5 and the R^2 values in Fig. 6 suggest that values of a_{hf} and a_{hT} (using weightings W_{hf} and W_{hT}) are too closely related for it to be useful to consider both weightings.

The R^2 values in Fig. 6 also illustrates that there is little apparent added value in precise measurement of higher vibration frequencies when considering a_h (W_h weighted) values. For the majority of industrial machines in the sample studied here, it makes little difference whether higher frequencies are included in the vibration measurement. Certainly, there appears little justification in including frequencies above 500 Hz in the W_h weighting.

It is important to recognise, that while this assessment does include large numbers of machines, covering a wide

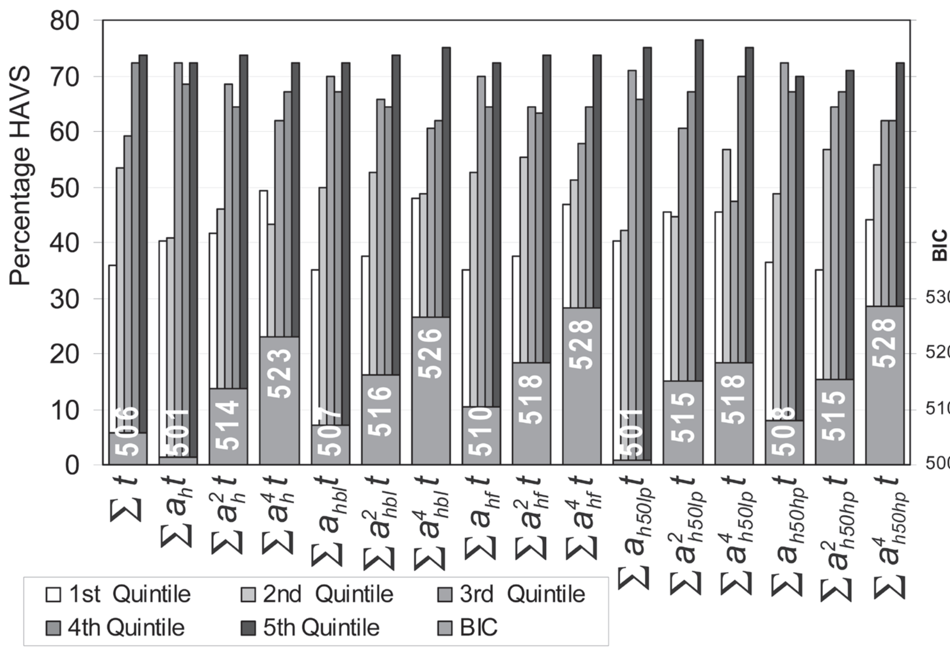

Fig. 7. Prevalence of HAVS by lifetime vibration dose quintiles and BIC values for five representative frequency weightings.

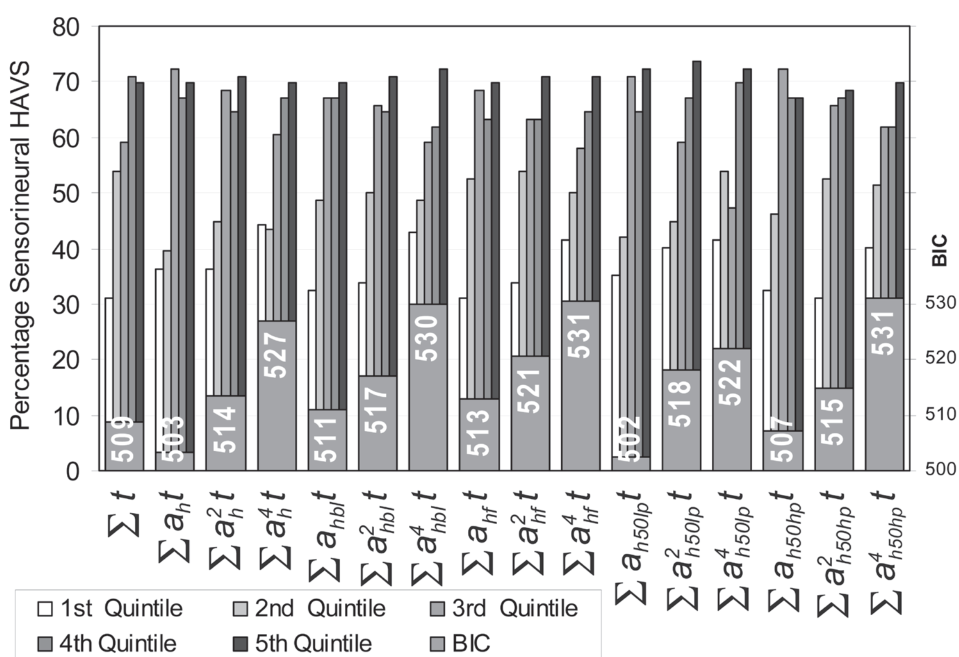

Fig. 8. Prevalence of sensorineural HAVS by lifetime vibration dose quintiles and BIC values for five representative frequency weightings.

range of machine categories not every machine category that exposes workers to hand-transmitted vibration is represented. There may be machine categories that are not included in this assessment that give substantially different responses from the weightings. The main concern here being very-high frequency dental drills which have been associated with HAVS-type injury but have frequencies many time higher than most other industrial machines[10]). There may be other biases in the HSL database, for example due to large numbers of measurement on certain

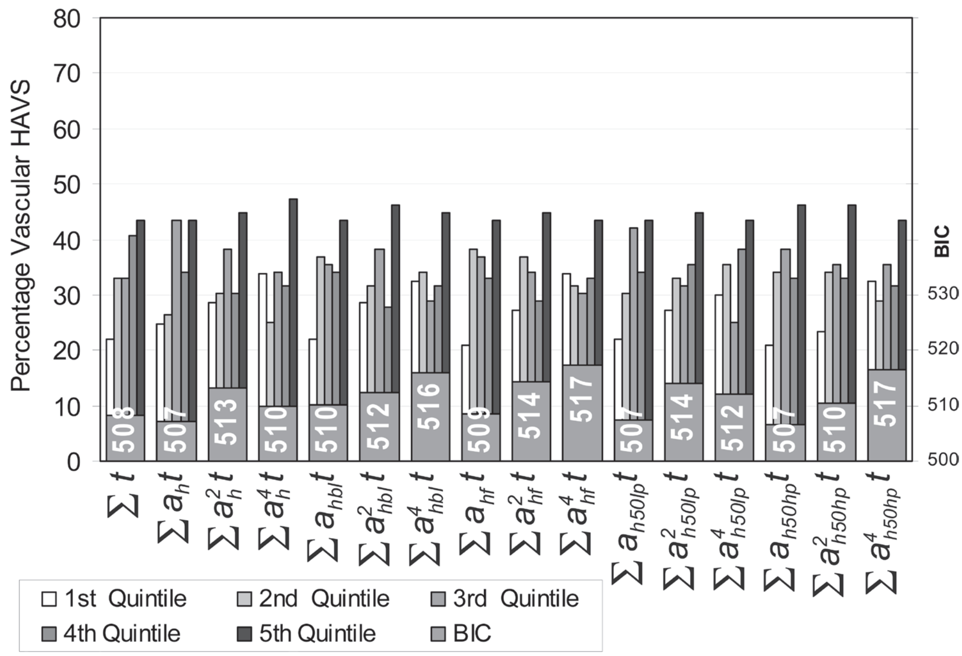

Fig. 9. Prevalence of vascular HAVS by lifetime vibration dose quintiles and BIC values for five representative frequency weightings.

tool categories (such as rock-drills and rotary hammers, impact drills and chainsaws) and much smaller numbers in others (for example linishers, polishers and belt sanders), see Table 1.

Alternative exposure assessments

Comparison of the dose measures using BIC suggests that values based on the first power of the two weightings W_h and W_{h50lp} provide the strongest indicators for developing any form of HAVS. The similarity between outcomes for HAVS and sensorineural HAVS is perhaps to be expected, since of the 224 subjects diagnosed with HAVS 217 had the sensorineural component of HAVS. For vascular HAVS there is no clear evidence to advocate using any of the evaluated dose measures.

The HSL HAVS data is based on 381 referral subjects who, in many cases, have reported the use of a wide variety of machines. Further work is being considered to refine the statistical analyses, for example to focus on cases that have less complex exposure histories, to include assessments of CTS cases and to investigate additional variants of the candidate frequency weightings.

Disclaimer

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