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Dose–response relationship between hand–arm vibration exposure and vibrotactile thresholds among roadworkers

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ABSTRACT

Background Testing of vibration perception threshold (VPT) at the fingertips as a quantitative measure of tactile sensitivity is a commonly used tool in diagnosing hand–arm vibration syndrome. There is limited research on dose–response relationships between hand–arm vibration (HAV) exposure and VPT on an individual level.
Aims Assess possible dose–response relationships on an individual level between HAV exposure and VPT at the fingertips.
Methods We assessed average daily vibration exposure (m/s^2A8) and cumulative lifetime HAV exposure for 104 participants from different departments in a road maintenance company based on vibration measurements and questionnaires. VPT was measured based on the technical method described in ISO 13091-1:2005 using octave frequencies 8–500 Hz. We investigated associations using linear regression models with significance level p≤0.05.
Results The participants were either exposed to rock drills (n=33), impact wrenches (n=52) or none of these tools (n=19). Exposure to rock drills and impact wrenches was associated with elevated VPT for all seven test frequencies in the second and fifth fingers of both hands. A dose–response with the daily exposure measure m/s^2(A8) was found based on 1.2 m/s^2(A8) for impact wrenches, and 5.4 m/s^2(A8) for rock drills. A stronger association was found with the cumulative exposure for rock drills compared with impact wrenches, and for the second finger compared with the fifth finger.
Conclusions HAV exposure was associated with elevated VPT, also at exposure levels below the common exposure action value of 2.5 m/s^2(A8). Lowering the HAV exposure can contribute to prevent increasing VPTs in these workers.

Key messages

What is already known about this subject?

- ► Exposure to hand–arm vibration from vibrating tools can cause vascular and neurological signs and symptoms related to hand–arm vibration syndrome (HAVS).
- ► A dose–response relationship between exposure and vascular symptoms has been established in the research literature.

What are the new findings?

- ► A clear dose–response also for neurological signs related to HAVS, measured as vibration perception thresholds (VPT).
- ► Increased VPT was found also for workers exposed on regular basis to low levels of hand–arm vibration.

How might this impact on policy or clinical practice in the foreseeable future?

- ► There is a need to protect workers and monitor their exposure to hand–arm vibrations also at exposure levels below the common exposure action value of 2.5 m/s^2(A8) for daily exposure.
- ► Screening exposed workers for increased VPT may be used as a method to identify sensitive individuals in a workforce and to help decide whether further actions to reduce vibration exposure in a workforce are warranted.

INTRODUCTION

Hand–arm vibration (HAV) is a common work-related exposure. In a national survey in Norway, 42% of the construction workers reported exposures to HAV at work on a regular basis.[1]

Exposure to vibrating tools at work may lead to hand–arm vibration syndrome (HAVS).[2] The pathophysiological changes of HAVS include changes in the blood vessels, sensory corpuscles and nerves.[3 4] After years of exposure, this commonly leads to symptoms of white fingers, numbness, tingling and reduced sensory function. Subjective neurological symptoms such as numbness and tingling of the fingers are linked to increased vibration perception threshold (VPT) of the fingers.[5] These signs and symptoms may cause reduced hand performance.[6] The most relevant exposure metric of vibration exposure causing vascular and neurological changes has not yet been fully established. The exposure limit value (ELV) and exposure action value (EAV) for exposure to HAV are in most countries set at an acceleration level of respectively 5 m/s^2(A8) and 2.5 m/s^2(A8) as a time-weighted average for an 8-hour working day. The acceleration is calculated using root mean square averaging. The frequency weighting curve (W_h) defined in ISO 5349-1 is commonly used.[7] This standard refers to estimations of dose–response that predicts vibration white fingers (VWF) which is a diagnostic term describing the most typical vascular symptoms of HAVS. Dose–response relationships

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between exposure to vibration and outcomes have been established for the vascular component of HAVS.[8–10] For the neurological component of HAVS the results have been less clear. To assess tactile sensitivity, testing of VPT is commonly used as a quantitative measure. There are studies showing dose–response at a group level but not at an individual level between HAV exposure and VPTs.[11 12] Studies by Sauni *et al* and Virokannas were indicative of a dose–response relationship also at an individual level.[13 14] A cohort study by Bovenzi *et al* showed a dose–response for thermal sensation but not for VPT.[15] In that study, VPT was measured at two frequencies. There is currently no consensus regarding neither design of test equipment, nor which and how many frequencies should be included to test VPT.[16] Most of the literature investigating dose–response is based on exposure assessments on a group level with self-reported exposure time, likely to bias associations.[17 18]

The present study is a cross-sectional analysis of the inclusion phase of a prospective cohort study of symptoms and signs related to exposure to handheld vibrating tools among roadworkers. In this study, we investigate the association between cumulative exposure to HAV and VPT. The aim of our study is to assess possible dose–response relationships between individual exposure to HAV from rock drills and impact wrenches and VPT tested at seven frequencies in the second and fifth fingers of both hands.

METHODS

Study design

A cross-sectional study design is used.

Inclusion of participants

We invited 108 workers employed in a Norwegian road maintenance company to participate in the study. The health examinations included a voluntary expansion of the ordinary health screening programme for the workers. All the rock face stabilisers and guardrail workers were invited to participate (n=60), because they were assumed to have the highest HAV exposure in the company. In addition, we invited workers (n=48) from other departments assumed to have no or low exposure to HAV. We did this to achieve an exposure contrast to the higher exposed workers. When investigating the exposure history of the participants in this group we discovered that many had similar exposures to impact wrenches or rock drills as the rock face stabilisers and guardrail workers, leaving only 19 workers unexposed to the two tools. Two workers among the rock face stabilisers refused to participate and one guardrail worker dropped out due to concurrent illness on the examination day. One participant among the unexposed did not show up for the scheduled appointment. The inclusion of subjects and baseline testing was performed during the period from November 2013 through March 2014.

Exposure assessment

We estimated vibration exposure based on field measurements done according to relevant parts of ISO 5349 part 1 and part 2.[7 19] The vibration metres Larson Davis HVM100 (Larson Davis, Depew, NY, USA) and Svantek SV106 (Svantek, Warszawa, Poland) were used for the measurements. Based on the measurements, we assigned the rock drillers an exposure to an average vibration magnitude of 17 m/s^2 during active operation of pneumatic rock drills, while the workers using battery-powered impact wrenches as their main tool were assigned an average exposure magnitude of 7 m/s^2. These levels correspond well to typical levels measured for these tools.[20] The average exposure time was estimated based on interviews with workers and time measurements in the field. A rock drill operator was exposed 47 min/workday on average, while an impact wrench operator was exposed for 15 min/workday on average. These exposures are equivalent to average daily exposure levels of 5.4 m/s^2(A8) for rock drill exposure and 1.2 m/s^2(A8) for impact wrench exposure.

To estimate lifetime cumulative exposure, information from questionnaires based on the VIBRISKS protocol (Risks of Occupational Vibration Exposures: Technical Report)[21] includes questions about exposure time per day, days per week, weeks per year and total years of exposure. Questions about the use of any vibrating tool other than the two main tools in the present and earlier occupational settings, as well as during leisure time were also included.

Vibrotactile perception thresholds

All the participants underwent a quantitative VPT test using VibroSense Meter (VibroSense Dynamics, Malmö, Sweden). The technical method was based on ISO 13091-1.[22] The second and fifth fingers on both hands were tested at seven frequencies: 8, 16, 32, 64, 125, 250 and 500 Hz, which include all the frequencies for VPT testing available with this instrument. The instrument uses the method of limits (often referred to as the von Bèkèsy method) with gradually increasing and decreasing sinusoidal vibration of a probe with a flat circular surface of 3 mm diameter.[23] The hand rests horizontally with the palm facing downwards. The finger to be tested rests with the pulp on the probe. A force indicator gives a light signal if the finger pressure is too high or too low to aid the patient in maintaining correct constant pressure during the test. The vibration magnitude of the probe increases in order of 3 dB/s, and the subjects press down a button with the opposite hand when they sense the vibrations and release the button when they no longer sense vibrations. This cycle is repeated and the vibration threshold for every frequency is calculated as the mean of four upper and lower limits of sensation. The test–retest reliability was found to be high in a study applying similar test equipment and methods.[24] The participants were not exposed to HAVs on the day of VPT testing.

Blood samples

Blood samples from the participants were analysed for parameters potentially relevant to the pathophysiology of reduced sensory nerve function. Whole blood was collected in parallel to VPT testing. Due to time constraints on the examination days, blood samples were obtained from only 93 participants. Analyses included haematology, glycated haemoglobin (HbA1c), C-reactive protein, carbohydrate-deficient transferrin (CDT), vitamin B_{12}, folate, albumin, alanine transaminase, glutamyl transpeptidase, cholesterol, caffeine, cotinine and thyroidal tests. All analyses were done by Fürst Medical Laboratory (Oslo, Norway). CDT was measured using capillary electrophoresis. A level of <1.7% was considered normal.[25] HbA1c levels were collected in EDTA tubes. Levels between 4.0% and 7.1% were considered normal. The method used for analysis of cotinine, caffeine and nicotine has been previously described in detail.[26] Information about body mass index (BMI) was collected in the questionnaires.

Statistical analysis

To investigate the associations between HAV and VPT we used multiple linear regression models in SPSS V.25 (IBM SPSS). In preparatory analysis, the potentially confounding factors BMI, cotinine, vitamin B_{12}, free T4, HbA1c and CDT were included in the regression models for all frequencies at the dominant second finger where the most significant associations were found. None of the information from the analyses of blood samples did confound the outcome. We classified age into intervals (20–29, 30–39, 40–49, 50–59 and 60–69). The age variable 60–69 was kept in the model as the analyses showed that only age at this level influenced the association, changing the estimate of effect with more than 10%. The number of hours multiplied with the typical acceleration level (hour·m/s^2) served as the main exposure measure for the operation of the two main tools. To investigate different outcomes based on which main tool the workers were exposed to, we split the independent exposure variable in two separate variables (rock drill exposure and impact wrench exposure). We also applied the acceleration level normalised to an 8-hour working day (m/s^{2}A8) multiplied by the number of days of operation for the two tools in models to investigate if the workers' exposure in relation to legislative EAV and ELV would provide any additional information. To enable log transformation, zero exposure to the main tools was substituted with hour·m/s^2=1. We log transformed the exposure measures to correct for skewness. Since the outcome is measured as threshold of perception measured in decibels, the models were built using a log-log transformed data set. Workers with injured or missing fingers were included in the analyses but only with the non-injured fingers.

RESULTS

Group characteristics

Of the 104 workers participating in the study, 33 were exposed to high acceleration levels from pneumatic rock drills, 52 were exposed to intermediate acceleration levels from battery-powered impact wrenches and the remaining 19 workers were unexposed to these tools, although some were exposed to ill-defined levels of exposure using different handheld tools (table 1).

Table 1 Characteristics of the study population

	Type of exposure*		
	Rock drills (RD)	Impact wrenches (IW)	No exposure to RD or IW
n	33	52	19
Age (years), mean (SD)	40.1 (13.1)	42.7 (12.7)	33.7 (11.1)
Body mass index (kg/m^2), mean (SD)	26.1 (2.8)	28.8 (3.8)	28.3 (5.8)
Smoking or tobacco snuffing, n (%)	23 (70)	29 (56)	8 (42)
Cotinine (ng/mL), mean (SD)	446 (417)	331 (444)	177 (260)
CDT (%), mean (SD)	0.7 (0.5)	0.7 (0.2)	0.7 (0.1)
HbA1c, mean (SD)	5.3 (0.3)	5.2 (0.3)	5.3 (0.5)
Vibration exposure level (m/s^2)	17	7	NA†
Vibration exposure (min/day)	47	15	NA†
Vibration exposure (hour·m/s^2), mean (SD)	13 219 (25 144)	2209 (2631)	1†
Vibration exposure (years), mean (SD)	11.4 (11.6)	15.4 (13.8)	NA†
Finger/hand injuries (%)	6 (18)	7 (13)	3 (16)
Vibration white fingers (%)‡	6 (18)	0 (0)	0 (0)
Finger numbness (%)	12 (36)	7 (13)	5 (26)

*n=6 had been exposed both to rock drills and to impact wrenches. These individuals are included in the table as exposed to rock drills. Information on total years of vibration was missing for one worker in the other work group. Blood samples were missing for two rock drill operators, seven impact wrench operators and one in the no exposure group.
†No exposure to hand–arm vibration (HAV) or rare/occasional exposure from other tools than rock drills or impact wrenches. To enable log transformation, zero exposure to the main tools was substituted with hour·m/s^2=1.
‡Diagnosed by an occupational medical doctor.
CDT, carbohydrate-deficient transferrin; NA, not applicable.

Effects at the group level

On a group level, for all tested fingers and frequencies, the VPTs increased with exposure, and were highest among the rock drill operators. The impact wrench operators had higher VPT for all fingers and frequencies compared with those not exposed to any of the two main tools (table 2).

Effects at the individual level

We identified a statistically significant association with dose–response between increasing vibration exposure and elevated VPT for all seven frequencies on both the dominant second and fifth fingers, on the non-dominant second finger and five frequencies on the non-dominant fifth finger (table 3). Using different measures of the product of time and acceleration levels, a slightly higher explained variance was obtained in the models using acceleration (m/s^2) times the cumulative hours of lifetime exposure calculated as two independent variables; one for exposure to rock drills and one for exposure to impact wrenches (online supplementary table 6a,b) compared with the combined exposure for the two tools (table 3).

Using the average daily exposure level (m/s^{2}A8) multiplied by lifetime exposure-days and including the exposure measure for rock drills (5.4 m/s^{2}A8) and impact wrenches (1.2 m/s^{2}A8) separately in models, then we found similar results for rock drills and somewhat weaker estimates of associations for impact wrenches, compared with lifetime hours times m/s^2. Based on exposure normalised to 8-hour daily exposure we identified an association in dominant second finger at all seven frequencies for rock drill operators and at four frequencies for impact wrench operators (table 4). Results from all four test fingers can be seen in online supplementary table 7a,b.

Variables based on information of self-reported lifetime use of other vibrating tools did not show any associations with the outcome (not shown). Among the covariates that were tested as potential confounders, ages 60–69 were shown to have an impact on the effect estimates, but none of the blood test results.

DISCUSSION

The average exposure to HAV among the rock drill operators exceeded the common ELV of 5 m/s^2(A8) for daily exposure. The impact wrench operators had low exposure to HAV; on average below both the common ELV and the EAV of 2.5 m/s^2(A8). Dose–response relationships between elevated VPTs at the second and fifth fingers of both hands and HAV exposure were shown. When splitting the cumulative exposure variable in two new variables based on tool exposure, the exposure measure for rock drills showed a stronger association with a clear dose–response relationship for both hands. The exposure measure for impact wrenches showed a weaker association, but still significant on some frequencies in the dominant hand.

For each added exposure unit of log acceleration·time (hour·m/s^2) the perception threshold was increased by 2.5 dB in the dominant second finger at the higher frequencies. The range of exposure was 1–100 000 hours·m/s^2 which equals 0–5 in the log-transformed variable. This means that a loss of VPT

Table 2 Vibrotactile perception thresholds, dB (SD) relative to 10^{-6} m/s^2, by frequency and finger

Test finger	Frequency (Hz)	Vibration perception thresholds, dB (SD): Exposed to: rock drills n=33	Impact wrenches n=52	No exposure to RD/IW n=19
Dominant hand				
Second finger	8	104.0 (6.8)	101.4 (6.1)	98.1 (4.7)
	16	109.3 (6.0)	106.8 (5.3)	103.6 (4.1)
	32	113.2 (6.7)	110.9 (4.1)	108.7 (4.7)
	64	111.2 (8.8)	108.4 (6.4)	104.9 (6.5)
	125	110.1 (8.4)	106.4 (6.4)	103.3 (8.5)
	250	119.3 (9.8)	114.7 (8.1)	109.7 (9.8)
	500	132.9 (12.5)	126.4 (8.6)	123.1 (7.8)
Fifth finger*	8	104.0 (7.7)	100.6 (5.0)	97.9 (5.2)
	16	109.8 (7.0)	106.3 (4.9)	103.8 (5.9)
	32	113.2 (7.4)	110.9 (5.5)	108.4 (6.0)
	64	112.5 (9.3)	110.6 (6.9)	106.2 (5.9)
	125	112.6 (13.1)	108.3 (8.9)	103.5 (7.2)
	250	120.8 (15.8)	115.3 (11.8)	111.4 (9.9)
	500	132.4 (14.1)	128.5 (11.9)	122.6 (10.3)
Non-dominant hand				
Second finger†	8	102.2 (6.4)	99.2 (5.3)	98.5 (6.0)
	16	107.9 (6.7)	104.9 (6.1)	103.5 (5.6)
	32	111.3 (6.9)	109.6 (5.9)	106.9 (4.4)
	64	109.3 (8.1)	106.2 (7.6)	104.1 (7.0)
	125	109.3 (10.1)	105.6 (8.5)	102.7 (8.5)
	250	116.7 (12.3)	113.0 (10.1)	109.1 (10.0)
	500	128.6 (14.1)	124.5 (12.0)	119.7 (9.9)
Fifth finger‡	8	103.2 (7.3)	99.2 (5.4)	98.1 (3.6)
	16	108.2 (7.2)	105.3 (6.0)	103.7 (3.8)
	64	111.7 (10.2)	109.0 (7.4)	107.7 (6.3)
	125	111.5 (13.8)	107.4 (9.2)	105.6 (7.6)
	250	119.1 (14.8)	113.2 (10.9)	109.7 (9.2)
	500	130.5 (13.8)	126.5 (11.6)	121.9 (9.9)

*n=51 for impact wrench operators, n=18 for no exposure.
†n=50 for impact wrench operators.
‡n=51 for impact wrench operators.
IW, impact wrench; RD, rock drill.

in the range of 0–12.5 dB could be explained by the exposure, meaning that the highest exposed workers showed a loss of 12.5 dB of the VPT compared with the lowest exposed. The clinical relevance of these numbers may be reflected by our study population where cases of VWF only were found among the highly

Table 4 Association between HAV exposure to rock drills and impact wrenches as separate variables and VPTs on dominant second finger: elevated VPT (dB) per 10-fold increase in days exposed to daily vibration in m/s^2(A8)

Frequency	Rock drill exposure: 5.4 m/s^2(A8) Dominant second finger (n=104)	Impact wrench exposure: 1.2 m/s^2(A8) Dominant second finger (n=104)
Hz	Unstandardised coefficient B (95% CI)	Unstandardised coefficient B (95% CI)
8	2.08 (0.96 to 3.20)*	0.91 (–0.05 to 1.87)
16	1.96 (0.99 to 2.94)*	1.03 (0.20 to 1.87)*
32	1.86 (0.91 to 2.81)*	0.88 (0.07 to 1.69)*
64	2.23 (0.88 to 3.58)*	1.01 (–0.15 to 2.17)
125	2.65 (1.28 to 2.83)*	1.27 (0.10 to 2.44)*
250	3.40 (1.74 to 5.06)*	1.70 (0.28 to 3.12)*
500	3.36 (1.50 to 5.21)*	0.74 (–0.85 to 2.33)

Models included age (using categories of age <60 and ages 60–69 years), rock drill exposure and impact wrench exposure.
*P≤0.05.
HAV, hand–arm vibration; VPT, vibration perception threshold.

exposed rock drillers, and the proportion of subjects reporting finger numbness was also highest in this group. For example, an elevation in VPT of 12 dB from 108 dB to 120 dB is equivalent to an elevation from 0.25 to 1 m/s^2. For the diagnosis of HAVS in the UK, VPTs are categorised into two: 'Possible disorder' and 'probable disorder'.[27] According to these criteria a VPT above 1 m/s^2 at the 125 Hz test frequency would be categorised as a probable disorder.

The stronger association between cumulative exposure from rock drills (m/s^2· hour) compared with exposure from impact wrenches could be explained by the much higher vibration magnitude of the rock drills. The characteristics of the rock drills that include peaks of high amplitudes could also be a contributing factor. A study comparing HAV from two different tools with different vibration characteristics (but same vibration magnitude in m/s^2) suggested that transient impulses can increase the risk of HAVS.[28]

It is possible that the weaker associations that we found for impact wrenches were caused by a possible baseline biological threshold where HAV exposure has no effect. Brammer[29] has proposed a baseline threshold of 1 m/s^2(A8) for vascular signs. This threshold could be similar for sensorineural signs. If exposure

Table 3 Association between HAV exposure and VPT: increase of VPT (dB) per 10-fold increase in exposure (hour·m/s^2)

Frequency	Dominant second finger (n=104)	Dominant fifth finger (n=102)	Non-dominant second finger (n=102)	Non-dominant fifth finger (n=103)
Hz	Unstandardised coefficient B (95% CI)	Unstandardised coefficient B (95% CI)	Unstandardised coefficient B (95% CI)	Unstandardised coefficient B (95% CI)
8	1.42 (0.57 to 2.27)*	1.47 (0.61 to 2.32)*	0.85 (0.02 to 1.67)*	0.97 (0.12 to 1.82)*
16	1.28 (0.53 to 2.03)*	1.40 (0.57 to 2.23)*	0.98 (0.08 to 1.87)*	0.94 (0.06 to 1.81)*
32	1.11 (0.37 to 1.84)*	1.14 (0.27 to 2.01)*	0.99 (0.14 to 1.84)*	0.53 (–0.40 to 1.46)
64	1.52 (0.50 to 2.55)*	1.83 (0.78 to 2.88)*	1.38 (0.31 to 2.45)*	1.10 (–0.06 to 2.26)
125	1.64 (0.59 to 2.69)*	2.16 (0.72 to 3.59)*	1.63 (0.35 to 2.91)*	1.59 (0.08 to 3.09)*
250	2.40 (1.09 to 3.61)*	2.39 (0.57 to 4.21)*	1.99 (0.46 to 3.51)*	2.26 (0.56 to 3.96)*
500	1.99 (0.56 to 3.43)*	2.76 (1.03 to 4.48)*	2.16 (0.42 to 3.90)*	2.07 (0.36 to 3.77)*

All associations were age adjusted, using categories of age <60 and ages 60–69 years.
*P≤0.05.
HAV, hand–arm vibration; VPT, vibration perception threshold.

below 1 m/s^2(A8) has too little energy to cause physical harm in human tissue, only a small percentage of the HAV exposure from using the impact wrenches (1.2 m/s^{2}A8) would be harmful compared with exposure from the rock drills (5.4 m/s^{2}A8).

The weaker associations between impact wrenches and VPTs of the non-dominant hands are also likely to be influenced by the fact that the battery-powered impact wrenches in use were tools operated by one hand, as opposed to the pneumatic rock drills normally operated using both hands.

A limitation of our study is the uncertainty regarding the lifetime exposure to HAV for some of the workers. We put much effort in the exposure assessment. However, it is challenging to achieve accurate lifetime exposure for HAV-exposed workers because there are many variables that are difficult to evaluate in retrospect, the most important being exposure time and vibration levels for the vibrating tools that participants in the study reported to be exposed to in the past. Variability of exposure resulting from effects of lack of maintenance of tools being used, external conditions such as hardness of the rock being drilled and individual working techniques are also sources of uncertainty. Such variability will most likely result in non-differential misclassification of the exposure, leading to diluted estimates of association.

Because this a cross-sectional study, we cannot conclude about causality between exposure and effect, even though there seems to be a strong relationship. Selection bias such as the healthy worker effect may be present. Acute symptoms such as numbness and tingling after vibration exposures of high magnitudes can be experienced among workers,[30] and it may be that workers finding these symptoms uncomfortable are more prone to change jobs. If these are the workers most susceptible to increased VPTs it might cover up an even stronger association. Chronic symptoms related to HAVS may also cause workers to change jobs.

Age confounded the association between exposure and VPT, but only among the participants aged 60–69 years. Many studies report an association between age and VPTs.[31–33] However, a study by Seah and Griffin did not find this association.[27] It is possible that a healthy worker effect in our study has concealed a stronger association with age.

Different methods of assessing vibrotactile thresholds have been published and these methods do not directly compare because of differences of the test equipment such as the size of the vibrating probe, the use of surround (supportive surface around the probe) and the use of automatic control of finger force against probe.[16] There are published reference values for VPTs based on testing equipment that resembles the one used in our study,[33 34] but not on identical equipment. However, because our study assessed workers with a variation of exposure to HAV, the results for the workers not having rock drills or impact wrenches as their main tool could be considered as reference levels. A strength of using this reference group is that they have a similar level of education and income. They are therefore likely to be of comparable socioeconomic background.

A recent proposal for consensus about diagnosing HAVS mentions two frequencies for assessing vibrotactile thresholds: 31.5 Hz and 125 Hz.[35] This is in agreement with proposed testing frequencies in ISO 13091-1.[22] However, there is limited research about the relevance of testing frequencies higher than 125 Hz.[15] A study by Rolke *et al*[36] showed that thresholds around 125 Hz were most sensitive to cumulative vibration exposure. Our study suggests that the greatest threshold elevations are identified at 250 and 500 Hz, and in most cases, the associations with exposure were also strongest at these frequencies. It could be hypothesised that an early prediction of harmful effects from HAV exposure can be found when assessing these higher frequencies. However, when looking at the VPTs for the workers exposed to impact wrenches it is difficult to conclude because it seems random which frequencies show statistically significant associations. It is possible that the different characteristics of HAV not accounted for by exposure measurement (such as frequency and impulsiveness) may cause different frequency patterns in the vibrograms of HAV-exposed workers. That could be an argument to include a wider range of frequencies for VPT testing. More research on the characteristics of HAV exposure and its possible influence on VPTs at different frequencies could be useful for early diagnosis or predictions about HAVS.

It is not surprising that the high exposure from rock drills causes elevated VPTs. It is however interesting that there is a significant association on some frequencies also for the much lower exposed impact wrench operators. Based on the exposure measurements and time measurements, the average time-weighted daily exposure is 1.2 m/s^2(A8) for the workers exposed to impact wrenches. The study by Sauni *et al*[13] also found a dose–response relationship between a relatively low daily HAV exposure of 1.6 m/s^2(A8) and VPTs in metal workers using impact wrenches.

We used the W_h weighting curve described in the ISO 5349 standards[7 19] for our exposure measurements. It has been proposed that frequency weightings with more weight on higher frequency spectra would be more appropriate for predicting vascular symptoms.[37] However, for predicting sensorineural changes such as higher VPT the W_h has been evaluated and found appropriate for vibrating tools with low vibration frequencies,[38] such as rock drills and impact wrenches.

Our validation of the workers' self-reported exposure time (by doing time measurements) resulted in a much lower exposure time as compared with the self-reports. This difference must be considered when comparing our results to studies only relying on self-reported daily exposure time. Workers' tendency to report too long exposure times is well known.[17–19]

The present study demonstrates the need to reduce workers' HAV exposure even at levels below the EAV of 2.5 m/s^2(A8). Elevated VPTs have been shown to be associated with patients' complaints of numbness and white fingers[30 37] and the elevated VPTs among the workers exposed to these relatively low exposure levels could be a sign of early stages of an occupational disease.

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