Dose–Response Relationship Between Exposure to Hand-arm Vibration and Health Effects among Metalworkers

RIITTA SAUNI1,2*, RAUNO PÄÄKKÖNEN2, PAULIINA VIRTEMA2, ESKO TOPPILA3,4 and JUKKA UITTI1,2

1Clinic of Occupational Medicine, Tampere University Hospital, FI 33521 Tampere, Finland; 2Finnish Institute of Occupational Health, PO Box 486, FI 33101 Tampere, Finland; 3Finnish Institute of Occupational Health, FI 00250 Helsinki, Finland; 4Department of Otorhinolaryngology, Tampere University Hospital, FI 33521 Tampere, Finland

Received 14 June 2008; in final form 24 August 2008; published online 14 November 2008

Objectives: The aim of this study was to explore the relationship of exposure to hand-arm vibration (HA V) and vascular, sensorineural and musculoskeletal symptoms and symptoms of carpal tunnel syndrome (CTS) in a population of Finnish metalworkers.

Methods: A questionnaire on HA V exposure and symptoms was sent to 530 metalworkers. Those who reported finger blanching, numbness or tingling of the fingers or symptoms of CTS were invited to further examinations (n = 133). Their cumulative lifelong exposure to HA V, the level of current exposure and the history of use of tools causing impulse vibration were evaluated. The association of different symptoms with the HA V exposure was assessed with logistic regression analyses adjusted for age and smoking. The vibration perception thresholds (VPTs) were tested according to ISO 13091-1:2001.

Results: The cumulative exposure index varied between 0 and 115 000 m² years d⁻⁴, the mean being 20 591 m² years d⁻⁴. The average of current daily vibration exposure was 1.6 m s⁻² and 39% of the participants had a history of exposure to impulse vibration. Of the respondents, 49% reported white fingers, 66% neurosensory symptoms, 56% symptoms of CTS and 75% musculoskeletal symptoms. The cumulative exposure index was associated with symptoms of white fingers [odds ratio (OR) 2.4–4.5], with symptoms of CTS (OR 4.6–6.1), with neurosensory symptoms (OR 5.7–17.3) and with musculoskeletal symptoms (OR 4.7–5.4). The risk of all these symptoms increased as the cumulative vibration dose increased. The history of exposure to impulse vibration had a significant effect on the occurrence of neurosensory symptoms (P = 0.024). The current exposure to HA V correlated significantly with all of the above-mentioned symptoms. The results of the VPT test were associated with the level of cumulative exposure to HA V.

Conclusions: There seems to be a dose–response relationship between the cumulative lifetime vibration dose of the HA V and finger blanching, sensorineural symptoms, symptoms of CTS and musculoskeletal symptoms of upper limbs and neck in the group of metalworkers of the study. The risk for neurosensory symptoms was the most significantly related to exposure to HA V and also to impulse vibration. Further studies are needed to confirm the present results also in other occupational groups taking into account the possible synergistic effect of workload as well.

Keywords: dose-response; exposure; hand-arm vibration; health effects

INTRODUCTION

According to different classifications, the health effects of hand-arm vibration (HAV) have vascular, neurological and musculoskeletal components (Griffin, 1990; Mason and Poole, 2004). Vascular disorders are characterized by attacks of cold-induced finger blanching, and it is the most extensively studied form of hand-arm vibration syndrome (HAVS). A dose–response relationship has been established between exposure to HAV and the risk of vibration-induced white fingers (VWFs) on the basis of several epidemiological studies (Gemne and Lundström,
1996; Bovenzi, 1998). The occurrence of VWF can be predicted on the basis of cumulative exposure to HAV according to the international standard ISO 5349.

Currently, there is less evidence on an exposure–response relationship for the exposure to HAV and neurosensory symptoms. It has been suggested that the causal relationship would be weaker than for VWF and not as linear as for vascular symptoms (Jorulf, 1986; Bovenzi, 1994). However, the neurosensory symptoms are a more complex entity to study because the symptoms are less well-defined than vascular symptoms and various clinical conditions may simulate the sensorineural component of HAVS. Especially the symptoms of carpal tunnel syndrome (CTS) are difficult to differentiate from those of HAVS (Gemne et al., 1987; Strömberg et al., 1999).

Vibration-induced musculoskeletal injuries affecting bone and joints have been reported in several studies (Hagberg, 2002). There is limited evidence that exposure to HAV and musculoskeletal symptoms of the upper extremities and neck and shoulder region are related (Bovenzi et al., 2005), and only some recent studies have suggested a dose–response effect (Åström et al., 2006; Wahlström et al., 2008). Although the ergonomic stress caused by hand-held vibrating tools may contribute to the pain in upper limbs, the vibration exposure may be related to muscle and joint symptoms per se. In an experimental study, vibration was shown to cause changes in muscle fibres (Necking et al., 1996). Especially those of HAV VS (Gemne et al., 1987; Strömberg et al., 1999).

If a dose–response pattern could be designed for all components of HAVS, it should be possible to define a level of exposure at which no adverse health effects would be expected. The aim of this study was to explore the exposure–response relationship of cumulative HAV exposure with vascular, sensorineural and musculoskeletal symptoms in a population of Finnish metalworkers.

METHODS

A screening questionnaire on symptoms of white finger attacks, numbness and tingling of the hands, decreased grip force or manual dexterity, or musculoskeletal symptoms of the upper extremities, neck or shoulder, as well as current exposure to HAV, was sent to a random sample of 530 metalworkers recruited from the register of the Metalworkers’ Union in the region of Pirkanmaa, Finland. Questions concerning HAVS with high sensitivity and specificity were obtained from Elms et al. (2005). Altogether, 285 (54%) of the 530 metalworkers returned the questionnaire after two reminders. Informed consent was obtained from each respondent. Ethics approval was obtained from the Ethical Committee of the Tampere University Hospital.

The criteria for further examinations were based on reported exposure to HAV and symptoms suggesting HAVS or CTS. The workers who reported finger blanching, numbness or tingling of the fingers or symptoms of CTS (n = 133) were invited to take part in clinical examinations in the outpatient clinic of occupational medicine in the Tampere University Hospital. A comprehensive questionnaire focusing on cumulative exposure to HAV and upper arm symptoms was sent to these workers. This study was based on the results of the questionnaires of 133 participants and their vibration perception thresholds (VPTs). Clinical examinations were performed by a physician according to a written protocol, and their results will be reported in a separate paper.

A participant was considered to have white fingers if he or she reported finger blanching in cold and the attacks had not begun before the age of 20 (primary Raynaud’s syndrome excluded).

A score of neurological symptoms was formed from 10 different questions ‘Have you had tingling in your hands that lasts over 20 minutes during exposure to cold, after the use of vibrating equipment or during attacks of white fingers (often, sometimes, never)?’, ‘Have you often had numbness in your hands that lasts over 20 minutes in exposure to cold, after the use of vibrating equipment or during attacks of white fingers (often, sometimes, never)?’, ‘Do you wake at night because of pain, numbness or tingling in your hands (yes, no)?’, ‘Are your hands numb, clumsy or weak in the morning (yes, no)?’, ‘Does exertion at work or at home increase the symptoms (yes, no)?’, ‘Does shaking or changing posture relieve the symptoms (yes, no)?’, ‘Have you noticed diminished muscle force in your fingers/hands/wrists during the last 2 years (yes, no)?’, ‘Have you had difficulties with manipulative dexterity, for example, buttoning your shirt (yes, no)?’, ‘Do you easily drop small items (yes, no)?’, ‘Have you had difficulties in picking up and handling small items (yes, no)?’ Each ‘often’ and ‘yes’ response was given one point.

A participant was considered to have CTS if he or she had at least three of the following four symptoms: hand numbness, awakening from sleep with tingling or numbness in hands during the last 2 weeks, pain in wrists during the last month or pain in hands at night during the last month.

Seven questions dealt with musculoskeletal symptoms in the upper limbs and neck: ‘During the last month (30 days), have you had pain in your hands during the day, pain in your hands at night, pain in your wrists, pain in your arms or elbows, pain in your shoulders, neck and shoulder pain, or neck and shoulder pain that radiates to your upper extremities?’.
Each ‘yes’ response was given one point, and a summed score was formed to describe the symptoms of the neck and upper arm.

**VPT**

The VPT test was performed according to ISO 13901-1:2001. The area of the vibrating transducer was 5 mm² (diameter 2.5 mm), and the pressure force to the finger responded to a mass of 20 g that equaled 0.2 N. The participant could control the intensity of the vibration [unit desibel (dB)] with reference value of 1 μm s⁻²] by a computer mouse so that, after the sensation, the intensity was recorded by the computer. The used vibration frequencies were 16, 31.5, 63, 125, 250 and 500 Hz. The measurement system was calibrated by a reference source before the measurements.

**Evaluation of vibration exposure**

The participants provided information on vibrating tools and their usage history in the questionnaire. The tools were classified by the researchers into percussive tools and non-percussive tools. A person was considered to have been exposed to impulse vibration if she or he had ever used percussive tools. The current levels of exposure, as well as the previous levels were evaluated using the vibration acceleration values from the European Union’s HAV Good practice Guide (European Union, 2006), a Swedish database (Umeå University, 2007), or were based on knowledge from measurements of the Finnish Institute of Occupational Health. The information stored in the Swedish database is compiled from both research reports and power tool catalogues. It contains Council of Europe (CE) declared values as well as field measurements. The European Union Guide provides data based on workplace measurements of total vibration values by Health and Safety Laboratory, UK, and Institut National de Recherche et de Sécurité, France, between 1997 and 2005. Data obtained from these sources were compared with our own field measurements by an experienced occupational hygienist (R.P.) to get an optimal approximation of vibration magnitude of the tools.

The cumulative HAV dose was calculated as an HAV index determined on the basis of the questionnaire, in which jobs, tools and active work time (hours/day, days/week and months/year) had been requested. The average daily (8 h) HAV exposure was calculated with the equation \( A(8) = a_m \sqrt{x/8} \), where \( a_m \) is the vibration acceleration (m s⁻²) of the machine and \( x \) is the daily exposure time (h). A cumulative exposure index, \( I \) (m² years d s⁻⁴), describing the total HAV exposure was determined by

\[
I = \sum A_i(8)^2 \text{ years d}
\]

where \( A(8) = \) average daily HAV exposure, years = exposure time in years and \( d = \) annual exposure time in days (d) and \( \Sigma \) equals the summing of scores for all used tools and exposures.

The participants were grouped into quartiles according to the cumulative exposure index. In the results, the two middle quartiles (Q₂ and Q₃) were combined. The impulsiveness of the exposure was taken into account as one variable. In addition, the level of current exposure was used as one variable.

**Statistical methods**

The analyses were performed with statistical package SPSS (SPSS 14.0 Inc., IL, USA). In the logistic regression model, the results were adjusted for age and smoking with symptoms of white fingers or CTS as dependent variables and cumulative exposure, level of current daily exposure (continuous variable) and impulse vibration (dichotomous variable) as separate explanatory variables. Age and smoking were used as covariates in the logistic regression. Age was a continuous variable and smoking was dichotomous (never smoker or stopped more than year ago; current smoker).

The scores of the questions concerning neurosensory or musculoskeletal symptoms were divided into three groups according to the quartiles of the cumulative exposure indexes (with quartiles Q₂ and Q₃ combined). A proportional odds model was used to assess the effect of the explanatory variables on the neurosensory and musculoskeletal symptoms. The explanatory variables and adjustments were the same as those presented earlier.

The means of the of VPT test results in the different exposure categories were plotted against the frequencies 16, 31.5, 63, 125, 250 and 500 Hz. A statistical analysis of the vibrotactile thresholds was performed with an analysis of covariance, in which the cumulative vibration exposure was the explanatory variable and age was a covariate. The pairwise comparisons were made with Fisher’s test for least significance difference to determine the groups between which differences were significant.

**RESULTS**

Data on cumulative exposure and the different symptoms were obtained from 133 participants. Two participants were not included in the analysis because of diabetes mellitus that may cause neuropathy. The mean age of the participants was 45.3 years. Most of them were male (n = 129, 98%). The number of current smokers was 48 (37%). The cumulative exposure index varied between 0 and 115 000 m² years d s⁻⁴, the mean being 20 591 m² years d s⁻⁴. The average of current daily vibration exposure was 1.6 m s⁻² and 51 participants (39%) had a history of exposure to impulse vibration. Table 1 shows the distribution of tools that the metalworkers used.
Table 2 presents the distribution of the different symptoms according to the quartiles of the cumulative exposure index. In the total group, musculoskeletal symptoms of upper limbs and neck were reported most often (3/4), followed by neurosensory symptoms (2/3) and about half of the participants had symptoms of white fingers or CTS.

The risk of white fingers increased as the cumulative exposure index increased (Table 3). The trend was clear, the odds ratio (OR) being 2.6 in the combined quartiles 2 and 3 ($P = 0.054$) and 5.5 in the highest quartile ($P = 0.004$). The OR for CTS symptoms increased in line with the cumulative exposure index, being 4.6 in the combined quartiles 2 and 3 ($P = 0.001$) and 6.1 in the highest quartile ($P = 0.002$).

Table 4 presents the association between cumulative HAV exposure and neurosensory and musculoskeletal symptoms. There was a statistically significant correlation between the increasing cumulative HAV dose and both neurosensory and musculoskeletal symptoms.

The current level of HAV exposure correlated positively with all types of the symptom types: the higher the current exposure, the higher the risk of adverse health effects. The exposure to impulse HAV was associated with the occurrence of sensorineural symptoms, but not with vascular or musculoskeletal symptoms or symptoms of CTS. Age or smoking status did not have a significant effect on any symptoms in this study.

The mean levels of the VPT tests increased as the frequency increased in all of the exposure classes and both hands (Figs 1 and 2). The differences between the VPT tests in the highest and lowest exposure quartiles were statistically significant in the 63, 125 and 500 Hz frequencies for the right hand and in the 125, 250 and 500 Hz frequencies for the left hand (Table 5). Statistically significant differences were primarily found between the highest and lowest exposure groups. For the right hand, at 16 and 250 Hz, the effect of exposure did not quite reach the limit of statistical significance. Age had an effect only on the left hand at 250 Hz, but still the vibration exposure was significantly related to the VPT test result.

Table 1. Distribution of tools used by the 133 metalworkers

<table>
<thead>
<tr>
<th>Name of the tool</th>
<th>Number of tools</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle grinders</td>
<td>196</td>
<td>36</td>
</tr>
<tr>
<td>Drilling machines</td>
<td>75</td>
<td>14</td>
</tr>
<tr>
<td>Slag hammers</td>
<td>69</td>
<td>13</td>
</tr>
<tr>
<td>Nut wrenches</td>
<td>47</td>
<td>9</td>
</tr>
<tr>
<td>Die grinders</td>
<td>28</td>
<td>5</td>
</tr>
<tr>
<td>Chipping hammers</td>
<td>26</td>
<td>5</td>
</tr>
<tr>
<td>Sanders</td>
<td>26</td>
<td>5</td>
</tr>
<tr>
<td>Sledgehammers and hammers</td>
<td>18</td>
<td>3</td>
</tr>
<tr>
<td>Saws</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td>Chain saws</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>Needle scalers</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td>Other tools</td>
<td>22</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>545</td>
<td>100</td>
</tr>
</tbody>
</table>

A worker could name several tools.

Table 2. Number of participants with the different symptoms according to the cumulative exposure index

<table>
<thead>
<tr>
<th>Symptoms</th>
<th>Cumulative index of HAV exposure</th>
<th>Total, $n = 131$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q$_1$, $n = 33$ (%)</td>
<td>Q$_2$–Q$_3$, $n = 66$ (%)</td>
</tr>
<tr>
<td>White fingers</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8 (25)</td>
<td>28 (42)</td>
</tr>
<tr>
<td>Neurosensory</td>
<td>10 (30)</td>
<td>49 (74)</td>
</tr>
<tr>
<td>CTS</td>
<td>9 (27)</td>
<td>42 (64)</td>
</tr>
<tr>
<td>Musculoskeletal</td>
<td>17 (52)</td>
<td>53 (80)</td>
</tr>
</tbody>
</table>

Q, quartile; Q$_1$, $< 3600 \text{ m}^2 \text{ years d}^{-1}$; Q$_2$–Q$_3$, $3600–31 000 \text{ m}^2 \text{ years d}^{-1}$; Q$_4$, $> 31 000 \text{ m}^2 \text{ years d}^{-1}$.

Table 3. Association of cumulative exposure to HAV, current exposure and the history of exposure to the impulse vibration with symptoms of white fingers and CTS (logistic regression, adjusted for age and smoking)

<table>
<thead>
<tr>
<th>Symptoms</th>
<th>Cumulative exposure index</th>
<th>Current exposure (mean daily acceleration value)</th>
<th>Use of tools with impulse vibration (yes/no)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OR, OR (95% CI)</td>
<td>OR (95% CI)</td>
<td>P-value</td>
</tr>
<tr>
<td>White fingers</td>
<td>1.0, 2.6 (1.0–7.7)</td>
<td>0.054</td>
<td>0.004</td>
</tr>
<tr>
<td>CTS</td>
<td>1.0, 4.6 (1.8–11.6)</td>
<td>0.001</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Q, quartile; Q$_1$, $< 3600 \text{ m}^2 \text{ years d}^{-1}$; Q$_2$–Q$_3$, $3600–31 000 \text{ m}^2 \text{ years d}^{-1}$; Q$_4$, $> 31 000 \text{ m}^2 \text{ years d}^{-1}$.
DISCUSSION

The results of our study suggest that a dose–response relation exists between cumulative HA V exposure and all of the studied symptoms of HA VS. In addition, exposure to impulse vibration was associated with a higher risk of sensorineural symptoms. Although the trends were clear, the results should be interpreted with caution.

It is possible that our estimation of the cumulative exposure is biased from two reasons: firstly, active work time was determined according to the self-evaluation of the workers and secondly, because tool vibrations vary greatly among workers, work tasks and tool loads; vibration values taken from a table may or may not reflect actual workplace exposures. The action time used in the estimations may be too high because there is evidence that people tend to overestimate the exposure time as the exact action time is difficult to estimate (Palmer et al., 2000). However, there is no alternative way to evaluate exposures that took place in the past. If the exposures were systematically overestimated, it probably would not have affected the dose–response manner of the relationship between exposure and symptoms.

The vibration acceleration data vary significantly for different tools and also for different work tasks, as can be seen from the European guideline (HAVS).
Good practice Guide, 2008). Because the number of the tools was very high (545 different tools), it was not possible to base the acceleration values on measurements. Also, much of the exposure originated from the previous work history and from tools that could not be measured any more. Thanks to technical improvements, vibration magnitudes of powered tools have lowered in recent decades. If the exposures were measured from the present machines, it could underestimate the exposures in the past.

We tried to minimize selection bias by sending the questionnaire through the Metalworkers’ Union because persons retired, unemployed or on sick leave but belonging to the Union were among the respondents. The respondents were on average 4.4 years older than the non-respondents (data from the Union register, data not shown). Young workers are more likely to be less exposed to HAV and also have fewer symptoms and thus are not so motivated to respond to this kind of questionnaire.

Confounding factors like smoking status, gender or age may explain some of the differences. In this study, smoking status and age were used as variables in the regression models, but they did not have a statistically significant effect on the ORs. Because there were only two women among the study group, gender was not included in the models. We ran additional analyses with adjustment for leisure-time exposure to HAV, but they did not change the conclusions of our study (data not shown). A limitation of our study was the inability to include any measure of physical workload. Workload increases musculoskeletal symptoms, but may also have an effect on sensorineural symptoms. The interpretation of our results should be done with caution in that respect.

The use of percussive tools has been considered to be a significant risk factor for HAVS (Starck, 1984). Some studies have shown opposite results in which there were no differences between exposures to impulse and non-impulse vibration as regards either acute effects or the prevalence of VWF (Schäfer et al., 1984; Mirbod and Inada, 1992). In our study, we found a significant association between impulse vibration and sensorineural symptoms, but not other symptoms of HAVS. The risk of other symptoms was increased, but not significantly. Metalworkers use a variety of vibrating tools, some of which cause impulse vibration, for example, impact wrenches and chipping hammers. However, the total hours of impulse tool use may not have been very high and, if so, it would explain the missing association between symptoms other than numbness and tingling. Impulse vibration was evaluated based simply on whether or not the workers had used tools emitting impulse vibration. If it had been possible to take into account the duration of the use of such tools, the risks could have differed.

Our findings confirm the results of previous studies in which an increase in vibration dose was associated with a significant increase in the occurrence of VWF (Jang et al., 2002; Griffin et al., 2003). Whether this kind of relationship applies also to neurological symptoms of HAVS has been unclear (Bovenzi, 1998; Mason and Poole, 2004). According to several epidemiological studies, numbness and tingling of fingers is in fact a commoner complaint than white fingers among workers exposed to HAV (Bovenzi et al., 1980; Futatsuka and Sakurai, 1986; Palmer et al., 1998). There is evidence for both the existence (Jang et al., 2002) and non-existence (Lundström and Hagberg, 1992) of a dose–response association between vibration exposure and neurosensory symptoms. The results of our study support the probability of a clear dose–response association.

Neurosensory symptoms can be tested by the VPT test which was used in the present study to confirm the results obtained from the questionnaire. The thresholds were higher in all the frequencies tested as the cumulative exposure increased as were also the scores of neurosensory symptoms. Our findings are in line with those of previous studies that have found a dose–response relationship between vibration exposure and VPT (Virokannas, 1992). However, there are also studies in which such an association was not found, at least not on individual basis (Lundström and Hagberg, 1992; Lundström and Strömberg, 1995). Our results support the assumption that the VPT test can separate persons according to their exposure to HAV. The small number of participants may explain the lack of statistical significance in some frequencies. Age alone did not affect the vibrotactile thresholds in our study, as was observed also earlier by Seah and Griffin (Seah and Griffin, 2008). Previous studies have shown contradictory results (Lundström and Hagberg, 1992).

In addition to vibration exposure, musculoskeletal disorders may also be related to neurological symptoms. In a 19-year follow-up of forestry workers, the prevalence of VWF decreased, but numbness increased from 23 to 40% (Sutinen et al., 2006). In that study numbness was associated with upper extremity musculoskeletal disorders. Metalworkers use vibrating hand-held tools, but also perform repetitive, forceful movements that may partly explain both their neurological and musculoskeletal problems. We found a significant independent dose–response like effect between increasing cumulative vibration dose and an increase in neck and upper limb pain, although we could not take the amount of workload into account. Various mechanisms have been suggested through which vibration may cause muscle pain. For example, vibration exposure may alter proprioception, and this phenomenon may cause workers use greater force than necessary to complete a task (Zakaria et al., 2002).
Workers who are exposed to HAV have at least a two times higher risk of CTS (Palmer et al., 2007). It has been suggested that vibration exposure may damage the median nerve in the carpal tunnel by causing myelin breakdown and interstitial and perineural fibrosis (Strömberg et al., 1997), but nerve entrapment in the carpal tunnel is another possibility and may be related to repetitive and forceful wrist movements. We found that the OR for CTS increased, along with the cumulative exposure index, up to 6.1 in the highest exposure category. Wieslander et al. (1989) recorded the number of years during which hand-held vibratory tools were used, whereas Nordström et al. (1998) calculated the number of hours per day, respectively. In these studies, a similar trend towards an increasing risk as exposure increases was suggested.

In conclusion, our study provides evidence that the cumulative lifetime vibration dose may be associated with VWF, sensorineural symptoms, CTS and musculoskeletal symptoms in the upper limbs and neck. Neurological symptoms seem to be the most strongly associated with vibration dose. A practical implication of the results is that the possibility of other symptoms than typical finger blanching should be taken into account equally in evaluations of HAV health hazards. Further studies are needed to confirm the present results also in other occupational groups than metalworkers taking into account the possible synergistic effect of workload as well.

**FUNDING**

Finnish Ministry of Social Affairs and Health; Department of Occupational Health and Safety.

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