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Relating Occupational Exposure to Persistent Health Effects †

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Abstract: The objectives of the Workshop are addressed using epidemiologic data from population groups in occupations involving exposure to hand-transmitted vibration and/or shocks. Pooled analyses demonstrate the limitations of the exposure–response relation in ISO 5349-1:2001, and that $A(8)$ is inappropriate for calculating the daily exposure to shocks as well as to continuous vibration. Alternative frequency weightings and metrics for daily exposure are explored.

Keywords: hand-transmitted vibration; shocks; exposure–response relations; frequency weighting; acceleration metric

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1. Introduction

This contribution to the Workshop addresses the Workshop's objectives from the perspective of epidemiologic studies of population groups whose members perform essentially the same work involving exposure to hand-transmitted vibration, or mechanical shocks (forestry chain saw operators, workers quarrying stone, etc.).

An initial question is whether the persistent signs and symptoms reported by persons whose hands are exposed to shocks, which include high-frequency vibration, are the same as those from exposure to continuous vibration within the frequency range considered in ISO 5349-1:2001 (i.e., 6.3–1250 Hz) [1]. The establishment of (visible) signs or (subjective reports of) symptoms limited to exposure to shocks could be a reason to establish a new metric for quantifying the different health effect(s). Occupational exposure to shock and high-frequency vibration is known to lead to the neurological symptoms and vascular signs associated with the hand–arm vibration syndrome (HAVS) [2–4]. The musculoskeletal component of the syndrome is also observed, as well as carpal tunnel syndrome (CTS), though there remain open questions surrounding the relation of such symptoms to vibration exposure and whether excess signs and symptoms of HAVS occur in occupations involving exposure to shocks.

In this paper, the development of signs and symptoms of HAVS common to occupations involving exposure to continuous vibration and/or mechanical shocks is considered. It focuses on the clinical development of the vascular component of HAVS, vibration-induced white finger (VWF), as an exposure–response relation for VWF is contained in an annex to ISO 5349-1:2001. This paper, in turn, focuses on the metric of daily exposure—the 8 h, frequency-weighted, energy-averaged, root mean square (r.m.s.) vector acceleration sum, $A(8)$—and enables its limitations to be evaluated [5,6]. Giving more weight to exposures involving shocks and high frequencies when assessing persistent health effects can be addressed by adjusting the frequency weighting applied to the metric expressing the vibration magnitude as well as by an alternate metric for the shock itself. The former is performed here by forming trial weighting functions [7]. Some suggestions for the latter are discussed.

2. Materials and Methods

Many studies have reported that the ISO exposure–response relation either over- or under-estimates the risk of developing VWF [5]. Central to any definitive evaluation of the persistent health effects experienced by different groups of workers exposed to shocks, or non-shock vibration, is a protocol designed to ensure the reliability of data selected for inclusion in the analysis. Here, the results of a comprehensive meta-analysis conducted by Nilsson et al. [8], in which 4335 publications from 1945 to the end of 2015 were reviewed, are used as source material for a pooled analysis. In order to derive exposure–response relations clearly compatible with the metrics in ISO 5349-1:2001, Scholz et al. applied further selection rules to the publications identified by Nilsson et al. [5]. This was primarily to ensure that the vibration measurements and daily vibration exposure had been determined according to the procedures in the standard. They then transformed the reported prevalences to a common prevalence of 10% in order to compare the data with the predictions of the exposure–response relation in ISO 5349-1:2001 [5,6]. Comparison with this exposure–response relation is obtained by a least-squares regression to obtain the best fit of the mean duration of employment exposed to vibration (D_y, in years) to reach a 10% prevalence of VWF, $D_{y,10}$, as a function of the $A(8)$ value for each population group, i.e.,

$$D_{y,10} = cA(8)^d \tag{1}$$

where c and d are fit parameters. The results of each epidemiologic study are given equal weight in this model.

In order to better represent the health effects of high frequencies and shocks, trial frequency weightings are constructed to explore the effect on VWF development of extending the upper frequency limit of the ISO frequency weighting. The method involves constructing frequency weightings for pairs of epidemiologic studies with the same risk of developing VWF, one of which involves exposure to shocks [7]. Thus, the population groups must have essentially equivalent latencies, and/or prevalences, and values of D_y. For a selected frequency weighting, the relative risk of developing VWF in the first population group compared to the second population group is then estimated using an expression for the daily exposure. The form of the relative risk, $RR_{f(trial)}$, for a trial frequency weighting, $f_{(trial)}$, is given by

$$RR_{f(trial)} = \left[\frac{a(1)_{f(trial)}}{a(2)_{f(trial)}}\right]^m \left[\frac{T(1)}{T(2)}\right]^s \tag{2}$$

where $a(1)_{f(trial)}$ and $a(2)_{f(trial)}$ are acceleration metrics for two power tools or machines that have been frequency-weighted by the trial frequency weighting, and $T(1)$ and $T(2)$ are the mean daily exposure times for the two population groups, respectively. As applied here, Equation (2) requires each population group to operate a single power tool or machine during the workday. In this formulation, the use of $A(8)$ as the daily exposure metric would result in $m = 1$ and $s = 0.5$. Alternative metrics for the stimulus are introduced into the calculation through $a(1)_{f(trial)}$ and $a(2)_{f(trial)}$, where a different frequency weighting and/or bandwidth for the stimuli, $a(1)$ and $a(2)$, can be defined.

3. Results and Discussion

3.1. Suitability of A(8) for Evaluating Daily Exposure Involving Shocks

The pooled analysis includes population groups in occupations that involve the near-daily exposure to one, or more, either non-shock- or shock-producing power tools or machines. The results for the onset of VWF may be summarized as follows.

(a) Regression analysis reveals that the best fit to the data possesses a gradient of $d \approx -0.5$ in Equation (1) [6], while that of the exposure–response relation in ISO 5349-1:2001 is close to $d = -1.0$. This result suggests that the exposure–response relation in ISO 5349-1:2001 may need to be revised.

(b) Different regression fits are obtained for occupations involving near-daily exposure to a single power tool (e.g., forestry workers using chain saws) as opposed to several power tools or machines (i.e., different values of a in Equation (1)) [5,6].

(c) For many of the studies included in the pooled analysis, similar values of D_y and $A(8)$ produce very different prevalences. This is observed irrespective of whether the occupation involved operation of a single or multiple power tools (or machines) during a workday. The implication of this observation, and the result in Section 3.1(b) above, is that the methods for calculating the daily exposure and for combining partial daily exposures in ISO 5349-1:2001, which are given by

$$A(8) = a_{hv} \cdot \sqrt{\frac{T}{T_0}} = \sqrt{\frac{1}{T_0}\sum_{i=1}^{n} a_{hvi}^2 \cdot T_i} \quad (3)$$

are inappropriate and need to be revised. In this equation, T_0 is a reference time for calculating daily exposure (8 h), and T is the mean time (in hours) group members are exposed to vibration with frequency-weighted, r.m.s., acceleration total value a_{hv} during a workday. For persons operating a range of power tools or machines during a workday, each for different times, the component exposures are summed as in Equation (3) for n tools and machines, where T_i is the time exposed to the ith tool or machine with acceleration total value a_{hvi}.

3.2. Including Higher Frequencies in the Calculation of Daily Exposure

Including frequencies above 1250 Hz in the calculation of daily exposure is an important consideration for evaluating human exposure to shocks. The results in Section 3.1, and those of a previous study [9], throw doubt on the validity of $A(8)$ for assessing VWF resulting from exposure to vibration or shocks and, in particular, on Equation (3). The construction of a metric for daily exposure to replace that in Equation (3) can be informed by considering the relation between a frequency-weighted measure of vibration magnitude and the daily exposure time. This is performed by comparing the relative risk of developing VWF in pairs of population groups in which essentially the same heath effect was reported, as described in the Methods section.

For this purpose, a population group operating chain saws with vibration-isolated handles was compared to one operating rock drills for hard-rock mining [10]. The vibration of the former possessed a frequency spectrum in which the handle acceleration consistently decreased in intensity at frequencies above 1 kHz, while that of the latter increased rapidly in intensity with frequency up to 4 kHz as a result of the shocks. At 1 kHz, the vibration of the rock drill was ~20 times that of the chain saw. Since the onset of VWF occurred after the same exposure time, D_y, in the two occupations, the relative risk obtained by applying different frequency weightings to these data can be assessed using Equation (2). The result should be unity (i.e., equal risk). For "flat" (i.e., frequency-independent) "weightings" when the daily exposure is constructed according to ISO 5349-1:2001, that is, by specifying $m = 1$ and $s = 0.5$ in Equation (2), the magnitude of the relative risk for these two populations is as follows.

(a) A flat frequency "weighting" from 6.3 to 1250 Hz (called the "unweighted" acceleration in some studies) produces $RR_{f(trial)} = 2.7$, and so overestimates the risk of exposure to the rock drills compared to the chain saws by a factor of almost three.

(b) Extending the flat frequency "weighting" from 6.3 to 10,000 Hz to include high-frequency vibrations results in an overestimate of the hazard of exposure to shocks by a factor of more than eight.

Clearly, merely extending the bandwidth to higher frequencies leads to incorrect estimates for the risk of developing VWF from exposure to shocks and high frequencies. However, a relative risk of close to unity is obtained when the frequency weighting in ISO/TR 18570 is employed (i.e., a flat "weighting" from 20 to 400 Hz) [11]. These results are obtained when the method for calculating daily exposure contained in ISO 5349-1:2001 is used, as already noted.

3.3. Suggestions for an Acceleration Metric for Shocks

As, clinically, population groups experiencing shock and non-shock exposure appear to develop the same vascular signs of HAVS, a *single* acceleration metric that can predict VWF from exposure to all tools and machines, both shock and non-shock, would seem preferable. From the results described above, this acceleration metric will need to satisfy the following conditions: (a) possess a frequency weighting that is not flat from 6.3 Hz to an upper frequency in excess of 1250 Hz, and (b) satisfy the condition $RR_{f(trial)} = 1$ in Equation (3) for a values of m and s other than those used in ISO 5349-1:2001.

At first sight, deducing or deriving an acceleration metric to satisfy these conditions would appear to be a daunting task. However, there is information in the literature with which to start. Dong et al.'s five-degree-of-freedom biodynamic model of the power absorbed in the fingers when grasping a vibrating handle would suggest a weighting that is essentially frequency-independent from about 20 to 400 Hz (−3 dB) [12]. At higher frequencies, the model suggests that the weighting will decrease by half with each successive doubling of frequency (i.e., the same gradient as that currently used in the frequency weighting of ISO 5349-1:2001 at frequencies above 16 Hz).

If an acceleration metric other than the r.m.s. acceleration is required to satisfy the condition $RR_{f(trial)} = 1$ when m and s assume values other than $m = 1$ and $s = 0.5$, a candidate constructed from so-called higher-order mean values may be suitable [13,14]. An attractive metric may be constructed from the time history of the vibration and/or shock(s) that takes the following form:

$$a = \frac{1}{K_r}\left[\frac{\sum_{i=1}^{N} a_i^{2(r+1)}}{\sum_{i=1}^{N} a_i^{2r}}\right]^{1/2} \tag{4}$$

In this equation, the acceleration time history is expressed by a digitized time series in which there are N samples, a_i. The index r has a value of, typically, 1, 2, or 3, and the K_r are numerical constants chosen so that when the a_i are in units of m/s^2, a approximates the r.m.s. acceleration in m/s^2 for a time series that does not contain shocks. In this way, the metric will yield r.m.s. accelerations that are close to those recorded on non-shock power tools and machines using present methods of measurement but will record an increased magnitude compared to r.m.s. for shocks. For a given shock, the increase in magnitude of the metric compared to a non-shock power tool or machine will depend on the value selected for r.

While metrics constructed from the ratio of higher-order mean values, as in Equation (4), will yield values related to the mean peak acceleration of transient vibrations, they will produce insignificant changes in values with changing repetition rates of such vibrations. Hence these metrics are unlikely to be suitable for assessing health effects from exposures to shocks, which may be expected to depend on the shock repetition rate (i.e., an increasing number of shocks in a given time interval is believed to increase the risk of developing most health effects). In these circumstances, a metric constructed from a single higher-order mean value may be preferred, such as the fourth-order mean value or root mean quad [13,15].

3.4. Relevant Daily Exposure Time for Shocks

There is evidence that the disruptions to tissues, neurological end organs, and nerve fibers caused by shocks persist for some time after the physical termination of the shock. The effects have been documented physiologically as a continuing reduction in vibrotactile perception long after the shock stimulus ceased. In one experiment, the temporary threshold shift was only reduced by 50% three minutes after the termination of exposure [16]. Hence, a biologically relevant time, possibly of the order of a minute, rather than the physical duration of a shock may be needed to appropriately characterize the health effects from isolated shocks lasting only a few seconds. An epidemiologic study involving workers using impact wrenches to tighten ~160 bolts per work shift recorded a physical exposure time of ~4 min/day [3], while a biologically relevant time could be more like 160 min/day. The conclusion of this study, using the physical exposure time to construct the daily exposure (Equation (3)), was that the risk of developing VWF is substantially underestimated for this workforce by the exposure-response relation in ISO 5349-1:2001. However, the underestimate would be eliminated if an exposure time of ~1 min were chosen to represent the biologically-relevant exposure time for each shock.

4. Conclusions

(1) A single acceleration metric would appear preferable for quantifying the risk of developing VWF in populations of workers exposed to either non-shock or shock accelerations.

(2) A frequency weighting that reduces the influence of increasing frequencies up to an upper frequency limit in excess of 1250 Hz is expected to be required to appropriately quantify the risk of developing VWF in persons operating power tools and/or machines that produce shocks and those that do not.

(3) Quantifying the risk of developing VWF from the near-daily operation of shock- or non-shock-producing power tools and/or machines is expected to require specification of a daily exposure that differs from the relation in ISO 5349-1:2001 (i.e., Equation (3)).

(4) A biologically relevant time rather than the physical duration of a shock time history may be needed to appropriately characterize the risk of developing VWF from near-daily exposure to shocks.

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