Vibration Exposure and Disease in a Shipyard: A 13-year Revisit

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Background *In a 1988 study of shipyard workers, a progressive association was observed between cumulative exposure to vibration and the vascular and neurological symptoms of the hand-arm vibration syndrome (HAVS). In 2001, after a decade of exposure reduction and ageing of the workforce, a second study at the same site was initiated.*

Methods *In 2001, 214 subjects were selected; they represented four current weekly vibration exposure time intervals—0 hr, >0 < 5 hr, ≥5 < 20 hr, ≥20 hr. The 1988 and 2000 cross-sectional populations were compared on the basis of exposure duration and current symptoms.*

Results *In 2001, the study population was 9.6 years older than the 1988 group. Current weekly exposure hours were similar in the low and medium exposure groups 2001 and 1988, but exposure was reduced by an average of 9.7 hr per week in the highest exposure group (≥20 hr) in 2001. Symptom severity was regressed polychotomously on estimated exposure (log cumulative hours); the OR was weaker in 2001 than in 1988 for sensorineural symptoms—1.44 [CI 1.04–1.98] versus 2.35 [CI 1.48–3.73]. This was also true for vascular symptoms—1.70 [CI 1.06–2.71] versus 3.99 [CI 2.27–7.01]. Vascular symptoms were more prevalent in the highest lifetime vibration exposure group in 1988 (68.7 vs. 43.2% in 2001); sensorineural symptoms were more prevalent in the least vibration exposed group in 2001 (52.6 vs. 20.7% in 1988).*

Conclusions *The prevalence of vascular symptoms associated with cumulative vibratory exposure was significantly greater in 1988, but neurological symptoms were more common at lower exposure levels in 2001. The presumption that reducing exposure duration alone is sufficient, in the absence of change in vibration magnitude, is not supported by the results of this study.* Am. J. Ind. Med. 45:500–512, 2004. *© 2004 Wiley-Liss, Inc.*

KEY WORDS: hand-arm vibration syndrome (HAVS); sensorineural; exposure magnitude; Stockholm Workshop Scale

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INTRODUCTION

The deleterious effects of hand-transmitted vibration from power tools on the peripheral nerves and small vessels of the upper extremity have been documented for almost a century. An extensive body of population-based studies has been summarized in both qualitative [Chetter et al., 1999] and structured reviews [Bernard, 1997]. In a 1988 study, Letz et al. [1993] found clear exposure–response associations for neurological and vascular hand and arm symptoms among a sample of American shipyard workers using power tools. Symptom prevalence resembled a then contemporary report on Italian shipyard workers, assessed with similar survey instruments [Bovenzi et al., 1980]. In a recently reported study of Korean shipyard workers, Jang et al. [2002] found 22.7% of exposed workers had vascular symptoms and 78.2% had sensorineural symptoms.

In 2001–2002, the principal investigator of the 1988 study (MGC) directed a re-investigation of the same shipyard. We revisit the association between vascular and neurological symptoms and current and cumulative exposure to hand-arm vibration by comparing subjects drawn from the 1988 and 2001 cohorts. The two cross-sectional investigations are separated by almost 14 years, and cannot be considered a true follow-up of an undiluted historical cohort. Widespread changes in work organization that have been the consequence of downsizing, streamlining, and broadening the tasks of the remaining workers, were particularly pertinent to this shipyard. In addition, recognition of the hazards of hand-arm vibration, in part influenced by the 1988 study, had been followed by increased surveillance, exposure dilution, and tool modification and replacement [Johnson et al., 1996; Kent et al., 1998].

Our hypothesis was that exposure reduction due to administrative controls and tool selection would reduce symptom prevalence.

A comparison of 1988 and 2001 survey instruments and shipyard demographics, a presentation of the association between prevalent symptoms and current and cumulative exposures, a comparison of exposures and symptoms in the two least altered departments (welders and shipfitters), and a multivariate analysis of risk factors and outcomes for the two study periods are discussed. Finally, there is a discussion of the difficulties inherent in historical studies in a climate of active intervention and a discussion of overall implications.

MATERIALS AND METHODS

Subject Selection and Questionnaire

The strategy for subject selection in the 1988 survey has been described elsewhere [Letz et al., 1993]. There was no medical testing. The 2001 survey instrument included all domains present in the 1988 survey with substantial additions. Although only responses to a limited set of questions common to the two surveys are reported here, the many dimensions of the 2001 testing protocol had important implications for comparability. Whereas both surveys were self-administered, the 1988 survey was completed off-site and took less than 45 min to complete. The 2001 survey was completed onsite with wage compensation by the employer and took up to 60 min to complete. The extended length and partial redundancy were concessions to history, collaboration, and international comparability. While most vibration-related health questionnaires are similar, there were small differences in wording of some questions shared by both surveys. Similar but substantively different worded questions were eliminated. Practically, this has meant that symptom questions were largely limited to the stages of the Stockholm Workshop Scale [Brammer et al., 1987a; Gemne et al., 1987], to a limited array of exposure questions, and to self-reported disease diagnosis by physicians.

Of more importance, dramatic changes in the organization of shipyard work prevented a replication of the sampling strategy that had been employed in 1988. While many of these changes will be explored quantitatively in the next section, it is sufficient to note that the full-time complement of dedicated pneumatic tools users (chippers and grinders) had been reduced from 460 in 1988 to 31 in 2001, virtually eliminating the highest exposure group. In addition, dedicated departmental task lines had been dissolved, with the consequence that entire departments that had been previously restricted from power tool use were now subject to intermittent patterns of use. Since a strict stratification based on department was now problematic, 2001 respondents were grouped by hours of current weekly exposure, no exposure, low exposure (<5 hr per week), moderate exposure (5–<20 hr per week), and high exposure (≥20 hr per week). Assignment of departments into no, low, moderate, and high exposure groups was based on job exposure ratings was completed by three independent groups—ship superintendents, union shop stewards, and Health and Safety department representatives prior to field assessment. Departments were selected to include a range of exposures, and differed significantly from those selected in 1988, due to work rule changes as well as vibration exposure. Sampling goals were assigned for individual departments, divided into task subgroups. Union stewards and shop superintendents assembled a master list of 360 eligible volunteers. Recruitment proceeded until populations were roughly equivalent in each exposure group. The final survey instrument was pilot tested extensively to insure that exposure questions were relevant to actual work processes and tools, and that questions were nonambiguous. The target was 220–230 subjects: 214 subjects completed their participation. As in 1988, participation was voluntary and confidentiality was maintained.

Signed informed consent was obtained from each participating subject in both 2001 and 1988. Study protocols were reviewed and approved by the Institutional Review Boards of the sponsoring institutions.

Tool Assessment

In 1993, the shipyard Health and Safety and Engineering staffs conducted their own survey of vibratory tools, comparing new and refurbished tools, various anti-vibration isolating materials, and different job tasks [Johnson et al., 1996]. The tests involved simulations on shipyard materials performed by representative members of the workforce. The American National Standards Institute Guide for the measurement and evaluation of human exposure to vibration was the methodological source [ANSI, 1986]. Accelerometers were mounted on tool handles, and results were reported for both frequency-weighted and frequency-unweighted accelerations. In all, 1,588 tool and tool head combinations and permutations were evaluated and archived. This data was reviewed in the early 1990s in order to assess typical tool accelerations and the effects of tool modifications.

Data Processing and Analysis

All responses from the 1988 survey were reclassified from three exposure groups to four, consistent with 2001 exposure categories. In addition, because we included co-morbidities in 2001 that did not exclude the use of power tools, 17 previously excluded subjects from 1988 with existing health disorders but without work restrictions were reassigned to the cohort, producing a final 1988 study population of 288. There were only six individuals that participated in both of the two surveys (four welders, a shipfitter, and a grinder). Therefore, we describe the two surveys as non-overlapping cross-sections.

Analyses were performed using SPSS and SAS statistical packages. Continuous data were summarized as means and standard deviations. Differences between group means were tested using one- or two-way analyses of variance and multiple comparison tests. Polychotomous logistic regression analyses were performed to assess the relationship between various independent variables and symptom stage progression. Exposures estimated in cumulative hours were transformed as common logarithms. Associations between age and exposure and between current and historic exposures were expressed as plain correlations.

RESULTS

Shipyard Demographics: 1988–2001

In 2001, the study participants differed significantly from their 1988 counterparts in regards to age and work duration. The average age in 2001 was 47.7 years (median = 48, range = 21–62), 9.6 years older than in 1988 (median = 35, range = 21–72). The 2001 workforce was experienced, having average work duration of 22.4 years (median = 23, range = 0.3–40). Apart from different approaches to participant selection, the increase in age is attributable to extensive downsizing of the workforce with an aggregate shift towards more tenured workers, due to union seniority rules. Employment in participating trades had declined by 78% (range = 66–93%), leaving an active pool of 1,708 workers compared to 7,624 in 1988. The major trades participating in the 1988 survey were grinders (116 respondents), welders (48), and shipfitters (46); the major trades taking part in the 2001 survey were outside electricians (54), welders (36), carpenters (35), and shipfitters (28). The reduced size of the available exposed workforce required high participation rates from selected departments in 2001. Shipfitters, grinders, welders, outside electricians, and laggers were all represented by sampling fractions in excess of 20%, while only grinders exceeded 20% in 1988. In the one case where the sampling fractions were comparable (grinders), the decimation of the department from 460 in 1988 to only 31 members in 2001 vitiated meaningful comparison.

In Table I, basic demographic and exposure information are compared for the 2001 and 1988 cohorts, and stratified into four categories representing current weekly vibration exposure duration. While these divisions produced roughly equivalent quartiles for the 2001 cohort, the over sampling of chippers and grinders in 1988 resulted in a significantly skewed representation in the high exposure group—21% of the 2001 cohort and 50% of the 1988 cohort. The seniority of the 2001 cohort is reflected in the cumulative years of vibratory tools use, which is on average 11.6, 12.6, and 9.8 years longer in the low, medium, and high exposure groups than for the 1988 cohort. The estimated average cumulative hours of vibratory tool use increased by 478, 132, and 49% between 1988 and 2001 in the low, medium, and high exposure groups. Current hours of weekly exposure were comparable for the low and medium exposure groups in 1988 and 2001, consistent with the intent of recategorization, but there was a substantial reduction in mean weekly hours of vibration exposure for the high exposure group—24.8 hr (SD 7.0 hr) in 2001 versus 34.1 hr (SD 6.9 hr) in 1988. Overall, current weekly hours of vibration exposure for the two cohorts, averaged over the four exposure groups, declined from 19.4 hr in 1988 to 9.1 hr in 2001. This is largely the result of sampling bias due to the elimination of the high exposure fraction in 2001, and it does not reflect a true shipyard average. Also notable is the absence of a true historically unexposed population in 2001. Thirty of 46 (65%) participants without current exposures to vibration had a history of past exposures to vibration, while none of those currently unexposed in 1988 had histories of past exposure. Cumulative historic exposures of the currently

TABLE I. Demographic Information and Vibration Exposure for the 1988 and 2001 Shipyard Cohorts; USA

	Vibration exposure groups							
	None		Low: >0 to <5 hr		Medium: ≥5 to <20 hr		High: ≥20 hr	
	1988	2001	1988	2001	1988	2001	1988	2001
Number of subjects	54	46	32	55	56	65	143	46
Age (SD)	38.5 (10.1)	47.0 (7.2)	35.6 (7.9)	47.2 (7.8)	38.6 (10.9)	49.2 (5.0)	36.9 (10.4)	46.8 (6.2)
Ethnic origin (%)								
White	90.7	91.3	93.5	90.9	89.3	93.8	82.4	87.0
Black	5.6	6.5	6.5	3.6	7.1	6.2	16.2	10.9
Other	3.7	2.2	0.0	5.5	3.6	0.0	1.4	2.2
Current smokers (%)	56.5	21.7	38.7	23.6	35.7	33.3	50.4	37.8
Anti-vibration glove use (%)	0.0	17.8	3.1	40.7	5.4	53.1	16.9	56.5
Current vibratory tool use (hr/week (SD))	0.0 (0.0)	0.0 (0.0)	1.8 (1.0)	2.2 (1.2)	10.4 (3.8)	9.8 (4.0)	34.1 (6.9)	24.8 (7.0)
Duration of exposure to vibratory tools (years ± SD)	0.0 (0.0)	9.1 (9.9)	9.0 (6.8)	20.6 (9.7)	10.6 (8.7)	23.2 (5.2)	10.4 (6.8)	20.2 (7.0)
Cumulative exposure to vibratory tools (hr × 1,000 (SD))	0.0 (0.0)	2.2 (6.0)	0.9 (0.9)	5.2 (7.3)	6.0 (6.6)	13.9 (14.0)	17.6 (13.1)	26.3 (26.6)

unexposed group in 1988 translate into 1.1 full-time working years of vibratory exposure based on an 8-hr work day, and an average 4.8 hr of vibratory weekly exposure, thus distributing their historical exposures between those of the current low and medium exposure groups.

There were several protective measures and behavioral changes with potential influence on health outcomes, introduced after the 1988 study. So-called "anti-vibration" gloves were worn by a majority (53%) of the 166 members of the 2001 cohort currently using vibratory tools, compared to only 11% of workers exposed to vibration in 1988. Overall, there was a decline in smoking prevalence from 47% of the participants in 1988 to 29% in 2001, with the decrease being greater in the less exposed groups.

In 2001 and in 1988, the correlation between age and current tool use were non-significant ($r = -0.02$ in 200, $r = -0.02$ in 1988), the exposure/age slope being -0.063 in 2001 and 0.006 in 1988. Neither survey showed the young to have greater use of power tools, or older shipyard workers to be spared their use. When age and cumulative tool use was correlated, cumulative exposures in the 2001 cohort tended to cluster at higher values than in 1988, as expected, and the age distribution was substantially shifted to the right. However, the overall dispersion of age and exposure data was similar for the two cohorts (RMSE = 7.23 in 200; RMSE = 6.04 in 1988.

In summary, the surveyed workforce had fewer current weekly hours of vibratory tool use and more cumulative years of tool use in 2001, compared with 1988, and increased age did not exclude the likelihood of heavy tool use.

Exposure Reconstruction

In Table II, vibration from several characteristic shipyard tools is compared together with anti-vibration adapted variants and a low vibration replacement. For purposes of comparison, identical tools from two other methodologically equivalent assessments are included. These were done by a private consulting group [BTI] [Whitaker, 1988] and by the National Institute for Occupa-

TABLE II. Frequency-Weighted and Unweighted Tool Accelerations; Shipyard, USA

		Weighted (unweighted) acceleration in m/s^2 (ANSI-1986)			
Tool type	RPM	BTI	NIOSH	Shipyard tested	Shipyard -tested (modified)
Large grinder	6000	2.7 (32.1)	8.9 (52.6)	4.17 (27.75)	3.28 (34.15)
Large straight burr	25,000	4.5 (94.2)	17.5 (183.3)	4.97 (202.05)	2.89 (152.54)
Low vibration burr				3.37 (27.21)	
Small burr	25,000	6.3 (157.7)	34.7 (244.5)	5.61 (146.81)	
Offset burr	18,000	8.0 (210.0)	47.8 (213.4)	9.31 (225.23)	

tional Safety and Health [NIOSH. Health Hazard Evaluation Report No HETA—348-2011, 1990]. Only a fraction of available tool and head combinations are included in Table II, but they demonstrate the scale of vibration reduction occurring between the 1988 and 2001 surveys.

In Figure 1, the reported cumulative hours of use for 13 principal vibratory tools are presented for both cohorts. In 2001 as in 1988, large grinders, burring tools, and offset grinders were the most heavily used tools. However, in 1988 the high exposure group came from a dedicated chipping and grinding department, and there was a virtual order of magnitude difference between heavily and moderately exposed tool users in their cumulative tool use. In 2001, the elimination of dedicated chipping and grinding resulted in cumulative use of the principal pneumatic tools being more evenly distributed among exposure groups. The similar use of multiple tools across different department trades highlights the problems associated with exposure reconstruction in

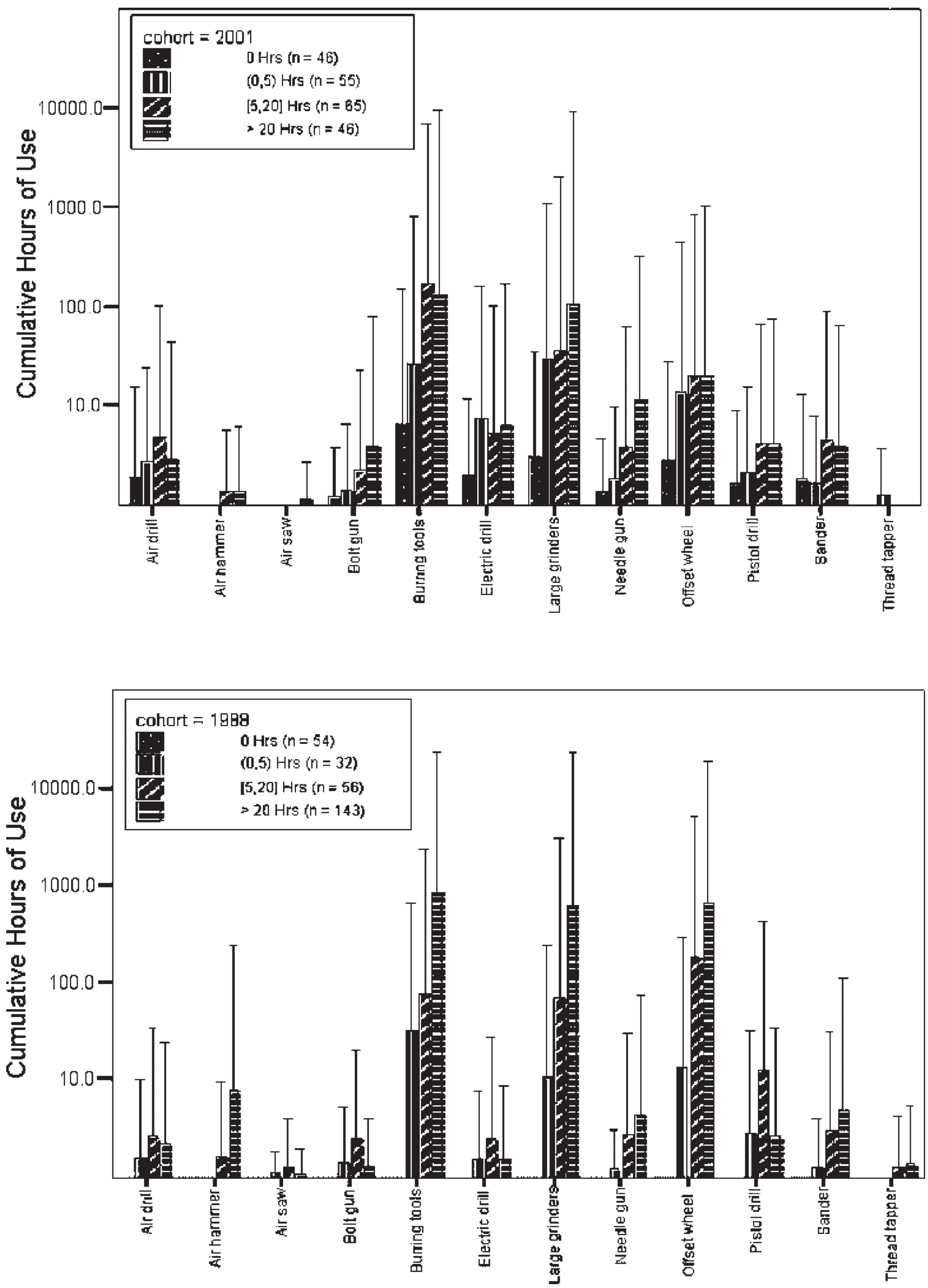

FIGURE 1. Mean (+1SD) cumulative use of pneumatic tools in 1988 and 2001 by current exposure group.

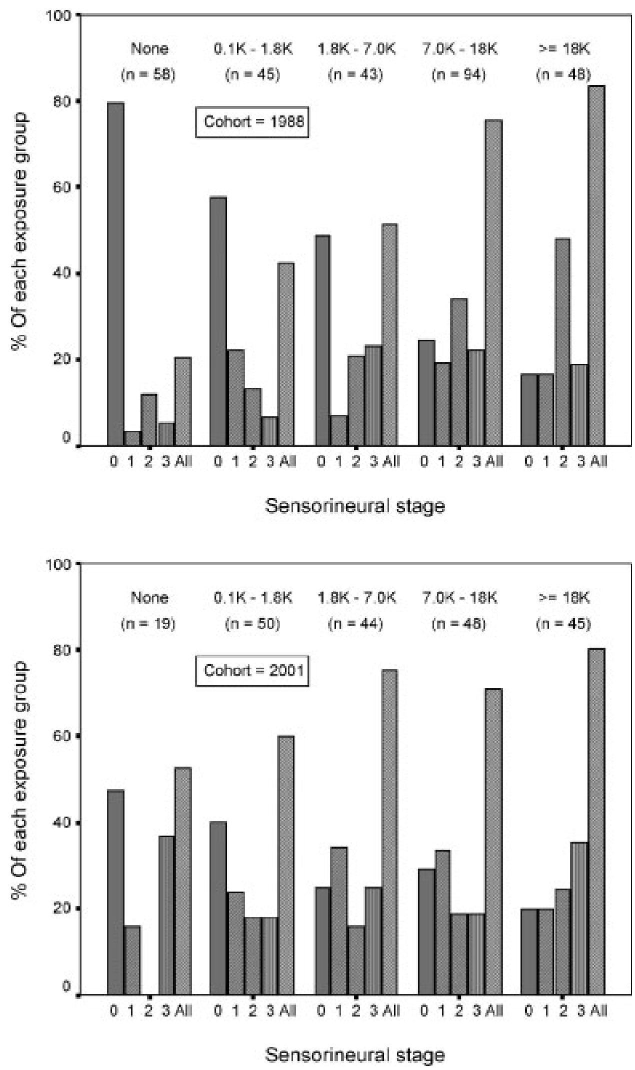

FIGURE 2. Cumulative exposure to vibration and sensorineural symptom stage. All = SN 1 + 2 + 3.

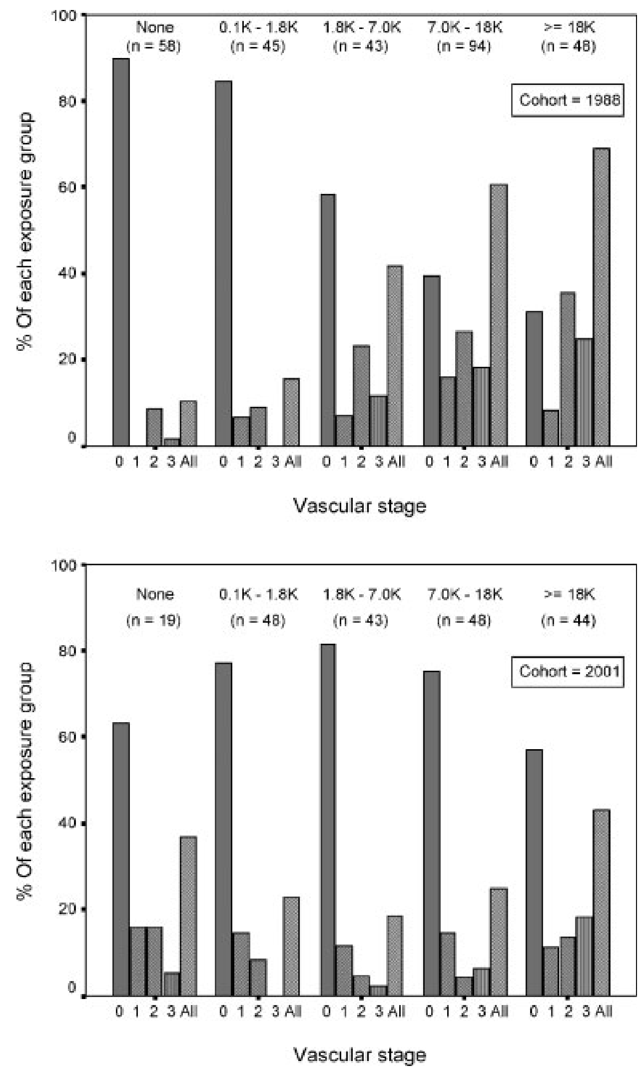

FIGURE 3. Cumulative exposure and vascular symptom stage. All = Vasc 1 + 2 + 3.

shipyard workers. In the 12 months prior to completion of the questionnaire, the average participant used 10.9 pneumatic tools (SD 7.0, range = 1–35), use being defined as a minimum of 30 min per month. In the four most represented departments, shipfitters averaged 17.6 tools (SD 6.0, range = 1–26), welders averaged 10.7 tools (SD 5.3, range = 0–27), electricians averaged 7.2 tools (SD 5.2, range = 1–19), and carpenters averaged 14.0 tools (SD 7.9, range = 1–35).

Exposure–Response Relationship

For purposes of comparability, symptoms are first reported as Stockholm Workshop Scale categories, either dichotomously (absent/present), or polychotomously as one of four outcomes. Exposures are presented as either cumulative or current. Current exposures follow the 4-part classification of: no, low, medium, and high exposure, expressed as weekly hours of vibration exposure. To assess cumulative lifetime exposure, the 2001 cohort was divided into five roughly equal quintiles of estimated lifetime hours of tool use—0, 100–1,800; 1,800–7,000; 7,000–18,000; and >18,000 hr. The 1988 cohort was redistributed accordingly. Two thousand cumulative hours translates into one full-time working-year.

Figures 2 and 3 depict the proportion of 2001 and 1988 study participants in each of the five cumulative exposure categories, segregated by Stockholm Workshop Scale symptoms. In 2001, sensorineural symptoms (Fig. 2) were already present in 52.6% of the population with no cumulative exposure, and this increased by smaller increments to 80% in those with more than 18,000 hr of cumulative exposure. Sensorineural Stage 2–3 symptoms were reported in near identical proportions by all exposure groups through

TABLE III. Symptoms and Current Weekly Exposure to Vibration; Shipyard Workers, USA

	Vibration exposure group							
	None		Low: >0 to <5 hr		Medium: ≥5 to <20 hr		High: ≥20 hr	
	1988	2001	1988	2001	1988	2001	1988	2001
Number	54	46	32	55	56	65	143	46
Complaints (% yes)								
White finger	7.4	27.3**	15.6	9.1	35.7	31.3	63.6	33.3**
Numbness and tingling	18.5	52.2**	40.6	57.4	58.9	79.7*	74.8	84.8
Loss of grip strength	18.9	60.0**	43.8	65.5*	41.8	70.3**	60.1	73.3
Vascular stage (%)	a*						b**	
Stage 0	92.6	70.5	84.4	87.3	64.3	68.3	36.3	60.0
Stage 1	0.00	13.6	6.3	10.9	8.9	11.1	12.6	17.8
Stage 2	5.6	11.4	9.4	1.8	14.3	12.7	32.2	6.7
Stage 3	1.8	4.5	0.0	0.0	12.5	7.9	18.9	15.5
Sensorineural stage (%)	c**							
Stage 0	81.5	47.8	59.4	40.7	41.1	20.6	25.2	15.2
Stage 1	3.7	23.9	21.9	24.1	17.9	28.6	15.4	28.3
Stage 2	11.1	4.4	12.5	18.5	21.4	22.2	37.7	21.7
Stage 3	3.7	23.9	6.2	16.7	19.6	28.6	21.7	34.8

a, b, c = significance test refers to χ^2 for inter-cohort comparison
$^*P < 0.05$.
$^{**}P < 0.01$.

18,000 hr (range = 36.0–40.9%), and it was only at >18,000 hr that a majority (60.0%) reported Stage 2–3 symptomatology. In 1988, the percentage of participants reporting sensorineural symptoms rose from 20.7% with no exposure to 83.3% when exposures exceeded 18,000 hr.

The pattern for vascular symptoms was very different (Fig. 3). Although vascular symptoms were unexpectedly high (36.8%) in the group with no cumulative exposure, 75.0–81.4% of participants were asymptomatic in cumulative exposure categories between 100 and 18,000 lifetime hours, and there was no increased trend of symptom severity with greater exposure. Only when cumulative exposures exceeded 18,000 hr did the proportion of vascular symptoms rise significantly (43.2%). By way of comparison, in 1988 vascular symptom prevalence was 68.7% in the highest lifetime cumulative exposure group. In 2001, 62% of all Stage 3 Stockholm Scale defined vascular cases were in the highest cumulative exposure group, whereas the comparable number was 34% in 1988. The comparison understates the true population impact, since the proportion of the 2001 cohort with >18,000 hr of cumulative exposure was 30% greater than in 1988.

In summary, when comparing 2001 with 1988 on the basis of cumulative exposure, reported sensorineural symptoms were more common in 2001 except in the two highest cumulative exposure categories where they were equivalent. Vascular symptoms were more prevalent in 1988, except in the cumulative lifetime non-exposure group, and accrued in number and severity as exposures increased, from 10.0% symptomatic without exposure and 68.7% symptomatic at >18,000 cumulative hours. For both sensorineural and vascular symptoms, there was already an observable effect at 1,800–7,000 hr of exposure, with 52.6% reporting sensorineural symptoms and 41.2% reporting vascular symptoms. Moreover, for each clinical stage (SN 1–3), symptom percentages increased over baseline. In 2001, only the highest cumulative lifetime exposure group provided evidence of an exposure–response effect.

The percentages of workers with selected symptoms, assembled according to their current weekly exposure categories, are presented graphically in Figure 4 and in Table III. The impressive associations between current exposures and vascular and sensorineural symptoms in 1988 are only partially reflected in 2001 (Fig. 4). In 2001, there was no significant similar increase in reported symptoms, except in the high exposure group. Most striking is the loss of exposure–response progression for vascular symptoms in 2001 and the high baseline and relatively flat progression of sensorineural symptoms. Because of the lack of a selective effect of age on current exposure and the small number of currently unexposed workers, cumulative and current exposure hours were strongly correlated (r = 0.53 in 2001, r = 0.69 in 1988).

The 2001 group without current weekly exposure had significantly higher rates of vascular and sensorineural

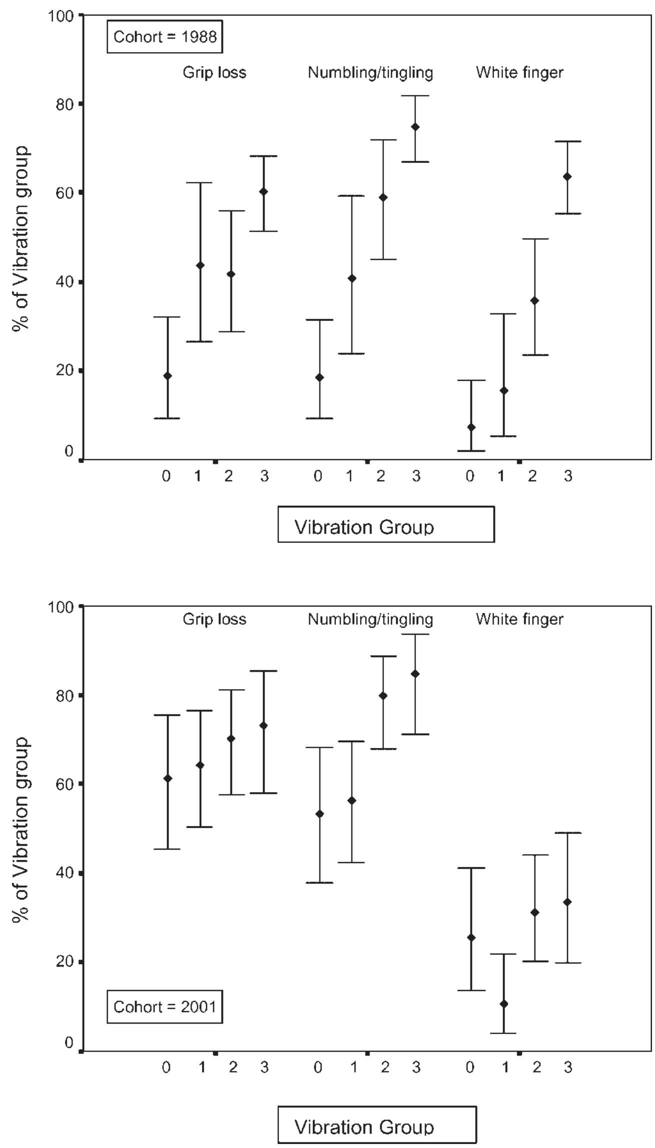

FIGURE 4. Self-reported symptoms and current vibration weekly exposure group. $0 = 0$ hr, $1 = >0$ to <5 hr, $2 = \geq 5$ to <20 hr, $3 = \geq 20$ hr.

symptoms and loss of grip strength than the 1988 counterpart (Table III). Most notably, a majority reported sensorineural symptoms (52.6%) or grip strength loss (60.0%), whereas 20% reported either of these symptoms in 1988. The low and medium exposure groups had comparable levels of vascular symptoms in 1988 and 2001, but grip loss and sensorineural symptoms were significantly greater for both exposure groups in 2001. Vascular symptoms were decidedly less prevalent in the 2001 high exposure group—33.3 versus 63.6%. In 2001, 74% ($n = 23$) of the participants with Stage 2–3 vascular symptoms were in the medium and high exposure groups, whereas the corresponding percentage in 1988 was 94% ($n = 88$). The comparison is somewhat misleading since the proportion of participants in the medium and high exposure groups was greater 1988, accounting for approximately one-third of the apparent difference.

In principle, less importance should be assigned to current exposures in assessing an exposure–response association for a chronic disorder. However, aside from preferential recall of more recent exposure, current use is also important because of potential recovery mechanisms and because symptoms that have, for example, a biomechanical component may be associated with acute vibration and work intensity.

Comparison Between Shipfitters and Welders

There were two departments, shipfitters and welders, which contributed at least ten subjects to the 2001 and 1988 cohorts, and can therefore be directly compared (Table IV). Estimated current weekly vibration exposure hours were 56% higher for shipfitters in 2001 (15.3 vs. 9.8 hr) and cumulative years of vibration exposure were 172% higher (21.5 vs. 7.9 years). For welders, current reported weekly exposure hours were 31% higher in 2001 and cumulative vibration exposed years were 503% higher.

Shipfitters were 42% more likely to have sensorineural symptoms in 2001 than in 1988, but the likelihood of vascular symptoms was reduced by 35%. Among binary measures, only loss of grip strength, which was 70% more prevalent in 2001, was statistically significant. There was no statistically significant difference between the proportional representation of either the vascular or sensorineural stages.

Compared with 1988, among welders there was no significant difference in either the overall prevalence of symptoms or the proportional distribution of symptoms according to vascular stage; sensorineural symptoms were elevated by 115% in 2001 compared to 1988, a significant difference, and the proportional distribution of symptom stages was also different between cohorts, particularly for the most advanced symptom stage. In 2001, 32.4% of the evaluated welders were in sensorineural Stage 3, whereas the corresponding level in 1988 was 8.3%. In both 1988 and 2001, welders reported half of the current weekly exposure hours and cumulative exposure hours of shipfitters, but both populations had in excess of a 500% increase in cumulative hours compared to 1988. Nevertheless, in 2001 there were no significant differences in sensorineural, vascular, or grip strength loss symptoms between welders and shipfitters.

Covariates: Other Risk Factors for Sensorineural and/or Vascular Symptoms

The relationship between symptoms and some risk factors is shown in Table V. In 2001 as in 1988, age and

TABLE IV. Demographics, Exposure, and Symptoms for Overlapping Trades (Shipfitters and Welders), 1998 and 2001; USA

	Shipfitter (226)		Welder (229)	
	1988	2001	1988	2001
Number of subjects (% of cohort)	46 (16%)	28 (13%)	48 (17%)	36 (17%)
Age (SD)	35.3 (8.2)	46.5 (7.7)**	34.8 (6.4)	49.3 (3.8)**
Ethnicity (%)				
White	91.3	96.4	85.4	86.1
Black	8.7	3.6	12.5	13.9
Other	0	0	2.1	0
Current smokers (%)	43.5	32.1	48.9	26.5*
"Anti-vibration" glove use (%)	2.2	39.3**	0.0	38.9**
Current vibratory tool use (hr/week (SD))	9.8 (9.4)	15.3 (7.9)*	5.8 (9.4)	7.6 (7.9)
Duration of exposure to vibration tools (years (SD))	7.9 (6.5)	21.5 (6.6)**	3.9 (6.2)	23.5 (7.6)**
Cumulative exposure to vibration tools (hr $\times$ 1,000 (SD))	4.4 (4.9)	24.2 (19.4)**	1.9 (3.8)	12.4 (19.8)**
Complaints (%)				
White finger	28.3	18.5	14.6	25.0
Numbing and tingling	47.8	67.9	29.2	62.9**
Grip loss	39.1	66.7*	34.0	82.9**
Vascular stage (%)				
Stage 0	71.7	74.1	85.4	75.0
Stage 1	8.7	7.4	4.2	8.3
Stage 2	10.9	14.8	8.3	11.1
Stage 3	8.7	3.7	2.1	5.6
Sensorineural stage (%)				
Stage 0	52.2	32.1	70.8	38.2**
Stage 1	15.2	28.6	12.5	26.5
Stage 2	21.7	21.4	8.3	2.9
Stage 3	10.9	17.9	8.3	32.4**

*$P < 0.05$.
**$P < 0.01$

cumulative exposure were correlated, as expected, as were current weekly and cumulative exposure. Smoking was unrelated to the duration of exposure in 1988 and, in fact, tenure was negatively associated with smoking prevalence in 2001. Nevertheless, smoking has proven to be an important predictor of vascular response in subjects with vibratory exposure and cold related symptoms [Ekenvall and Carlsson, 1987; Cherniack et al., 2000], so it is a potential covariate of reported symptom outcomes. As in 1988, polychotomous logistic regression was applied, with the outcome being Stockholm Workshop Scale stage and regressor variables being age, smoking, overhead work (an important postural variable in 1988) and a measure of vibratory exposure.

TABLE V. Risk Factors and Hand-Arm Symptoms; Shipyard Workers, USA

	Neurologic stage						Vascular stage					
	1988			2001			1988			2001		
	OR	95% CI		OR	95% CI		OR	95% CI		OR	95% CI	
Age	0.992	0.968	1.016	1.012	0.969	1.056	1.005	0.979	1.031	0.987	0.934	1.044
Current smoker	1.846	1.127	3.023	0.972	0.540	1.751	2.401	1.421	4.056	4.162	2.052	8.442
Arms above shoulders	3.007	1.685	5.366	1.664	0.892	3.103	2.015	1.070	3.794	1.414	0.585	3.416
Log10 cumulative exposure hours	2.350	1.482	3.725	1.439	1.044	1.983	3.990	2.272	7.006	1.698	1.063	2.714

The odds ratios (OR) for all of the vibration exposure variables—current weekly hours, cumulative years, cumulative hours, and the common logarithm of cumulative hours—were significantly different from zero; in 2001 as in 1988, the common logarithm of cumulative hours of exposure to vibration provided the best fit for all outcome variables. The fit was better in 1988 than in 2001. The common logarithm of cumulative exposure hours was more strongly associated with sensorineural symptom stage in 1988 than in 2001—estimated OR 2.35 versus 1.44. The relationship was more pronounced for vascular symptom stage—estimated OR 3.99 in 1988 and 1.70 in 2001. That is, each log unit of cumulative vibratory exposure in 1988 was associated with more than twice the level of stage progression observed in 2001. There was no statistically significant effect of age on the polychotomous outcomes variables or vascular or sensorineural stage. Smoking was not associated with sensorineural stage in 2001, unlike 1988 (estimated OR of 1.85; 95% CI 1.13–3.02); however, the association of vascular stage (VWF) with smoking was even greater in 2001 (estimated OR of 4.16; 95% CI 2.05–8.44 in 2001, and estimated OR of 2.40; 95% CI 1.42–4.06 in 1988). Working with arms above the shoulder was associated with both sensorineural and vascular stage only in 1988.

The possibility that symptom differences are mirrored in clinical diagnoses was assessed by comparing self-reported symptoms with anamnestically determined physician diagnoses of pertinent clinical conditions in 1988 and 2001. Participants were four times more likely report a physician diagnosis of CTS in 2001 (28.6 vs. 6.3%) but were not significantly more likely to have been diagnosed with Raynaud's Phenomenon (3.4 vs. 2.1%). While the concomitants of age-related susceptibility and symptom awareness, variability of recollections of tool use, and professional or patient bias cannot be sorted out with this type of recollected data, it suggests that CTS was, at least, more likely to be diagnosed after 1988 in the 2001 cohort.

DISCUSSION

Before attempting to interpret the results, implicit study limitations should be recognized. First, this was not a longitudinal cohort study, but rather two cross-sectional studies of the same workplace with different subjects. Second, the sampling frame was different in the two surveys, resulting in different occupational distributions, neither being a proportional sample of the larger workforce. Third, differences in the location and duration of testing may have biased results in unknown directions. Fourth, exposures and health effects were obtained solely by questionnaire, presenting the possibility of common-instrument bias. Fifth, because the 2001 study was designed for later longitudinal examination of exposure and response relationships, workers with historic vibratory exposure, who were currently restricted from vibration due to hand-arm conditions, were deemed ineligible.

Exposure Reconstruction

The decision to rely on years and hours of tool operation as exposure surrogates reflects an active decision not to reconstruct tool specific exposure matrices. Although, it has become conventional to combine personal exposure histories with limited tool simulation data to create an individual exposure matrix, we believe that the limitations of the method have been so extensively documented, its inclusion here was more likely to shed darkness than light. Bovenzi [1998] explored the limitations of this approach showing that differences between exposure models constructed in this way were slight, thus suggesting that measurement uncertainty overwhelmed the attempted formulation of individual exposure. In a compiled analysis of multiple cross-sectional studies, where exposures were constructed across models accounting for frequency, magnitude, and duration, Griffin et al. [2003] provided supportive evidence for a qualitative approach to exposure reduction that ironically would also favor a measureless approach over crude exposure reconstruction based on simulated measurement. They found a linear relationship between rms acceleration and total duration of exposure that appeared to obviate the more complex second power method introducing "energy equivalent" exposures. Their conclusions emphasized the primacy of exposure duration reduction in preventing symptoms. Our study suggests a quite different conclusion, since neither current nor cumulative hours of exposure had equivalent effects in 1988 and 2001. Nevertheless, when we considered the mixture of available measurements, the limitations of extending simulations to individual daily or cumulative exposure, and the diversity of tool use among shipyard workers, it seemed that any effort to reconstruct exposure from the available data along the form of $\Sigma_i a_i^n t_i$ would have limited validity, where a_i is the acceleration magnitude for tool i, and n is an integer.

While the precise estimation of vibration magnitude is elusive, as demonstrated in Table II, vibration control efforts were substantial. In addition to the shipyard-derived examples, additional appreciation of vibration levels from the 1980s can be obtained from the two external independent studies of principal shipyard tools studies performed in 1988 [Whitaker, 1988; NIOSH. Health Hazard Evaluation Report No HETA—348-2011, 1990]. The NIOSH study was performed on-site using routinely serviced tools in actual job tasks while the Whitaker study involved new tools, tested in a laboratory simulation. Thus, these differ from and elaborate on the field simulations performed by shipyard staff. There is considerable variation between individual operators, tool tasks, performance related to tool age and maintenance.

Hence, these types of limited tool profiles should be regarded as more suggestive than definitive for estimating exposure. Nevertheless, the 1993 data suggest that vigilant maintenance (refurbishment), use of isolating materials, and replacement with lower vibration tools collectively reduced the weighted acceleration in the 1990s compared with the 1980s.

Exposure Versus Dose

We use the term exposure to indicate an external source of vibration, measured in terms of magnitude, frequency, and duration. We use the term dose to indicate the modification of physical exposure within the human body by such factors, as hand transmission, rates of recovery, and effect threshold [Checkoway et al., 1989]. None of these components of tissue effect can be derived from the current data. In part because of evidence of a recovery function in other studies (as well as historic trends in tool modification), an allowance might be made for different time histories of exposure, which may serve as the substrate for dose simulation models that differentiate between each working day [Brammer et al., 2001], and exposures that accumulate over months and years [Bovenzi et al., 1995]. Griffin et al. [2003] found little evidence or utility for such an association. Our results only partially concur with the observations by Bovenzi [1998] and Griffin et al. [2003] that metrics for attributing cumulative exposure are interchangeable. In fact, the fit in the logistic model was somewhat better for cumulative hours than years, although goodness of fit does not necessarily improve the overall strength of the model. In almost all model variations, the hierarchy of fit for symptom stage was log cumulative hours > vibration-years > current weekly vibration exposure.

While this would appear to support the obvious point that current exposure is a less relevant indicator in a chronically acquired disease, there being a threshold effect, it was also notable that the association of exposure-years with symptoms was weaker than cumulative hours. Other investigators have shown greater unreliability in estimating cumulative hours of work, particularly when exposures are intermittent [Palmer et al., 2000], but a systematic bias towards estimation of hours of vibratory tools exposure would not necessarily affect the goodness of fit of the exposure model. All of this suggests, but certainly does not prove, that the differences between current weekly use and crude employment statistics, observed in our study, are meaningful and that historic use patterns are an even better predictor of symptoms.

Effects of Exposure Reduction

The 2001 survey provides evidence that job rotation, erosion of traditional trade union job categories, and elimination of dedicated vibratory tool use lead to increased exposure for former low exposure groups and elimination of the highest exposure group. Where there is comparable departmental representation [e.g., welders and shipfitters], the estimated current exposure hours were higher in 2001 than in 1988 (Table IV). Due to seniority provisions and a large decrease in the number of employed workers, the overall age and cumulative exposure rose dramatically in all employment and exposure groups. Even among the remaining nine shipyard grinders in the 2001 cohort (not presented in Table IV), while the current exposure hours were reduced from 33.4 to 25.4 compared with 1988, the cumulative exposure hours and vibration-years doubled—36,100 versus 18,200 hr, and 23.1 versus 11.2 vibration-years. At the same time the weighted acceleration was reduced by tool replacement or modification.

If Griffin et al. [2003] are correct, vascular symptoms should have been more advanced in 2001, reflecting increasing cumulative exposure. Our results suggest something different. VWF, the conventional benchmark for vibration related symptoms, did not increase with cumulative exposure except for total exposure in excess of 18,000 hr. The prevalence of symptoms in the currently unexposed group would suggest, however, that symptom reporting may have been age influenced, or at least different from 1988. While symptom exaggeration or a reporting bias is possible, there are other explanations for more frequent reporting of cold induced symptoms, such as a high prevalence of entrapment neuropathy [Nilsson, 2002]. In 1988, a vascular effect was detectable from 1,800 to 7,000 hr of cumulative exposure, as a 165% increase in cold-related symptoms compared with baseline exposure. In 2001, there appeared to be a doubling of the induction time for a significant increase in symptoms over a general baseline. Thus, it appears that a new hire could function for at least 20 years at current weekly exposure before experiencing an increase in vibration-related vascular symptoms. This is a crude assessment that does not account for exposure intensity or patterns of shipyard tool use that differ from those in the survey. An effect from exposure modification can be inferred. A threshold effect at lower exposures, mitigating cumulative exposure, can also be postulated.

Could other more individualized factors, such as decreased smoking or personalized risk reduction, either from lifestyle change or biomechanical risk reductions explain the higher exposure duration threshold? Smoking was reduced in 2001 compared with 1988, but paradoxically its OR was increased for vascular symptoms in 2001. Since smoking was not correlated with greater exposure hours, a consistent explanation is that exposure magnitude reduction had an even more dramatic effect than first appears but was less effective in the residual population that both smoked and continued its use of vibratory tools. It is also worth pointing out that workforce selection is an unlikely explanation. Seniority related selection actually restricts dilution from younger healthier workers and also reduces survivor bias, since there is no modified duty for the symptomatic injured. Age, as noted, did not appear to be a factor in either the prevalence or severity of vascular symptoms in 1988 or in 2001. The postural variable of working with arms above the shoulder, while significant in 2001, was less important than in 1988. Interestingly, it had less effect on the logistic models in 2001 than in 1988, suggesting that the presumably higher 1988 vibratory exposures may have magnified other modifiers of effect. So-called ''anti-vibration'' glove use had increased between 1988 and 2001, though there was no evidence that glove use protected against symptoms. While glove use was associated with more symptoms in initial cross-tabulations and correlations, the association disappeared when vibration exposure was entered in the regression, indicating that the initial association was most likely due to the higher probability of using ''anti-vibration'' gloves if exposed to vibration.

Vascular symptoms tend to be more specific to vibratory tool exposures than neurologic complaints since the latter can originate from pathologies proximal to the hand and may overlap with other non-vibratory causes, such as biomechanical risks. A high prevalence of exposure-independent symptoms, particularly sensorineural symptoms, suggests that other factors may be contributing to patterns of numbness and tingling, and reduced performance and hand strength, either independently or in concert with vibration. It should be recalled that some subjects without current vibration exposures had considerable previous exposure. The concurrence between current exposures and sensorineural symptoms in 2001, compared with 1988, may indicate a more temporal or episodic pattern of disease. It is consistent with the observation by Farkkila et al. [1988] that, among forest workers, reduced tool vibration had less of an effect on neurological symptoms than vascular symptoms, because of the persistence of biomechanically influenced disorders, such as CTS. Self-reported prior physician diagnosis of CTS had a monotonic association with current exposure, and increased to over 35% of workers in the highest exposure group in the 2001 survey. This suggests but does not prove an effect from a current work process (symptom amplification), rather than from a cumulative exposure. It is more suggestive of a cumulative trauma disorder, especially a nerve compression disorder with its activity related paroxysms, than a small fiber neuropathy which is less intermittent and subject to mechanical exacerbation. The small fiber neuropathy associated with direct injury from vibration tends to have a more fixed quality [Lundström and Lindmark, 1982; Brammer et al., 1987b].

CONCLUSIONS

Taken in isolation, the 2001 results support a somewhat more sanguine estimation of vibration health risks than was the case in 1988. The exposure–response relationship is still strong: for each log unit of cumulative exposure the estimated OR for sensorineural stage progression was 1.44; it was 1.70 for vascular stage progression. If the elevated symptoms at zero current exposure are the assumed baseline, there was no detectable increase in symptoms before 18,000 hr of cumulative exposure.

The evidence supports the efficacy of qualitatively driven exposure reduction, even if exposure–response mechanisms are not transparent. The multi-dimensional character of sensorineural complaints calls for future studies able to differentiate between pathologies and between the differential effects of coincident risk factors. The optimistic view that reducing exposure duration alone is sufficient, in the absence of considerations of change in vibration magnitude, is not supported by these data, where a significant (but undefined) level of engineering control has been introduced with apparent affect.

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