Hand-arm vibration syndrome and dose-response relation for vibration induced white finger among quarry drillers and stonecarvers

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Abstract

Objectives—To investigate the occurrence of disorders associated with the hand arm vibration syndrome in a large population of stone workers in Italy. The dose-response relation for vibration induced white finger (VWF) was also studied.

Methods—The study population consisted of 570 quarry drillers and stonecarvers exposed to vibration and 258 control stone workers who performed only manual activity. Each subject was interviewed with health and workplace assessment questionnaires. Sensorineural and VWF disorders were staged according to the Stockholm workshop scales. Vibration was measured on a representative sample of percussive and rotary tools. The 8 h energy equivalent frequency weighted acceleration ($A(8)$) and lifetime vibration doses were calculated for each of the exposed stone workers.

Results—Sensorineural and musculoskeletal symptoms occurred more frequently in the workers exposed to vibration than in the controls, but trend statistics did not show a linear exposure-response relation for these disorders. The prevalence of VWF was found to be 30.2% in the entire group exposed to vibration. Raynaud's phenomenon was discovered in 4.3% of the controls. VWF was strongly associated with exposure to vibration and a monotonic dose-response relation was found. According to the exposure data of this study, the expected percentage of stone workers affected with VWF tends to increase roughly in proportion to the square root of $A(8)$ (for a particular exposure period) or in proportion to the square root of the duration of exposure (for a constant magnitude of vibration).

Conclusion—Even although limited to a specific work situation, the dose-response relation for VWF estimated in this study suggests a time dependency such that halving the years of exposure allows a doubling of the energy equivalent vibration. According to these findings, the vibration exposure levels currently under discussion within the European Community seem to represent reasonable exposure limits for the protection of workers against the harmful effects of hand transmitted vibration.

Adverse health effects resulting from the use of vibrating tools in the stone industry have been reported since the beginning of this century. In 1911, Giovanni Loriga, an Italian physician, first described the occurrence of episodes of tingling, numbness, and whiteness in the fingers and hands of stone and marble cutters and carvers who used barrel shaped air hammers without a handle and throttle valve.¹ Later in 1918, Alice Hamilton reported that 89.5% of 38 limestone cutters of Bedford, Indiana, United States, had attacks of finger blanching (defined as "spastic anemia affecting the arterioles of the fingers and hands")² resembling the digital ischaemic phenomenon described by the French physician Maurice Raynaud in 1862. A personal review of the available scientific literature showed that in the last 80 years about 20 epidemiological surveys of vibration induced disorders among stone workers have been performed.¹⁻¹²

Italy produces more stone than any other country in the world (7.2 million tons in 1991). In Italy great varieties of ornamental stones such as marble, travertine, porphyry, granite, and serpentine are excavated in the quarries and processed in the mills. In recent decades there has been limited implementation of technical measures aimed at reducing the risk from exposure to excessive vibration in the stone industry. Taylor *et al* who revisited the limestone quarries of Bedford after a 60 year interval,⁷ found that no change in the design of the air hammers used by the stonecutters had taken place since the 1918 Hamilton survey. We did similar observations in a previous study of travertine quarry drillers and stonecutters who mainly operated percussive pneumatic tools.¹⁰ In the present study, the occurrence of hand-arm vibration syndrome was investigated in a large sample of quarry drillers and stonecarvers working in several districts of Italy. The term hand-arm vibration syndrome is used to refer to the collection of peripheral neurological, vascular, and musculoskeletal symptoms that are recognised to affect the upper extremities of workers exposed to vibration. As the characteristics of vibration exposure in the stone industry were found to be stable over time, mainly with respect to the type and design of the pneumatic tools used by the stone workers, the relation between vibration exposure and the various components of the hand-arm vibration syndrome was also studied.

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Materials and methods

SUBJECTS

The study population consisted of 828 active stone workers employed in nine districts of North and Central Italy, where quarrying and stonemasonry have an important role in the local economic life. The group exposed to vibration included 145 quarry drillers who used rock breakers and rock drills and 425 stonemasons processing stone blocks in the mills. Of the stonemasons, 188 (group A) used only rotary tools (angle grinders), and 237 (group B) used both rotary and percussive tools (angle grinders and light stone hammers). The remaining 258 stone workers formed the control group, which consisted of manual polishers and machine operators not exposed to hand transmitted vibration. All the stone workers employed in six districts participated in the survey ($n = 578$, 69.8%), whereas in the three other districts they were selected on the basis of a random sampling of the quarries and mills located in the respective geographical areas ($n = 250$, 30.2%). In total, 42 quarries and 99 stone mills were surveyed.

MEDICAL INTERVIEW

Each stone worker was interviewed by health and workplace assessment questionnaires similar to those proposed by Pelmear *et al.*¹³ The questionnaires were given by occupational physicians carefully trained to question the stone workers, employed in the various survey sites, in a standardised fashion. The questionnaires contained items on the subject's personal, medical, and work history. Sensorineural (SN), vascular, and musculoskeletal disorders of the upper extremities were investigated. Sensorineural disturbances in the fingers and hands were staged according to the following symptom scale, adopted from Brammer *et al.*: stage SN0 = no SN symptoms; stage SN1 = intermittent numbness with or without tingling; stage SN2 = persistent numbness and reduced sensory perception; stage SN3 = persistent numbness, reduced sensory perception, and impaired manipulative dexterity.¹⁴ Vibration induced white finger (VWF) was graded according to the clinical stages of the Stockholm scale: stage VWF0 = no finger blanching attacks; stage VWF1 = occasional attacks affecting only the tips of one or more fingers; stage VWF2 = occasional attacks affecting distal and middle (rarely also proximal) phalanges of one or more fingers; stage VWF3 = frequent attacks affecting all phalanges of most fingers.¹⁵ The staging of both neurological and vascular symptoms was made separately for each hand. The simultaneous presence of the following symptoms and signs was considered to be suggestive of carpal tunnel syndrome (CTS): (a) paraesthesia, numbness, or pain affecting the median nerve distribution of the hand(s), (b) nocturnal exacerbation of the sensorineural symptoms, (c) Tinel's sign present, or positive Phalen's test.¹⁶ Further questions concerned history of musculoskeletal disorders such as persistent pain of the shoulders, elbows, wrists, and hands, muscle weak-

ness, and Dupuytren's contracture. Both the workers exposed to vibration and the controls were carefully questioned about leisure activities, previous muscle or tendon injuries, bone fractures, constitutional white finger, systemic diseases (diabetes, connective tissue diseases, cardiovascular, neurological, or joint disorders), and regular medical treatment. Cigarette smoking was expressed as pack-years ((cigarettes/day/20) $\times$ years smoked). Alcohol consumption was estimated in g/day.

MEASUREMENT AND EVALUATION OF VIBRATION EXPOSURE

The stone workers exposed to vibration reported a detailed description of the hand held power tools used during their career. Professional usage of vibrating tools was expressed in terms of operating h/day, days/y, and total years separately for each tool. Only 22 subjects (3.9%) had been engaged in previous jobs with vibrating tools for a short time (0.5–2 y). A workplace tool assessment showed that vibrating tools of the same type and model were used in the quarries and mills, as a very limited number of manufacturers supply the Italian stone industry with portable vibratory tools. The tasks performed by the drillers and carvers have been described in detail elsewhere.^{7,10}

Hand transmitted vibration was measured on the handles of a representative sample of rock breakers ($n = 3$), rock drills ($n = 5$), stone hammers ($n = 5$), and angle grinders ($n = 4$) used by skilled stone workers under actual operating conditions. Hand held rotary and percussive tools of varying size and type were chosen to measure vibration arising from the most frequent work operations performed during stone quarrying and carving. Vibration acceleration measurements were made in the orthogonal directions X, Y, and Z according to the International Standard ISO 5349.¹⁷ Three accelerometers (Brüel and Kjaer 4374) were firmly attached to an adaptor (Brüel and Kjaer UA 0894) tightened around the tool handle by means of suitable clamps. To avoid zero direct current shifts in the transducer output, a butyl rubber sheet (Brüel and Kjaer DS 0707) was interposed between the adaptor and the handle of percussive tools. Before vibration was measured, the transducers were calibrated (Brüel and Kjaer 4294), and the accelerometer connecting cables were carefully taped to avoid cable movements producing triboelectric noise. The accelerometer signals were amplified by charge amplifiers (Brüel and Kjaer 2635) and recorded on a four channel digital recorder (Teac RD-101T). The acceleration recordings were analysed in the laboratory by a real time analyser (Larson and Davis 2800). From the one third octave band frequency spectra (6.3–1250 Hz), the magnitude of the root mean square (rms) of both unweighted acceleration and frequency weighted acceleration according to ISO 5349 was obtained. The vector sum (a_{sum}) of the rms unweighted and weighted accelerations was also calculated by the following formula:

$$a_{\text{sum}} = (a_{x,h}^2 + a_{y,h}^2 + a_{z,h}^2)^{0.5} \text{ m/s}^2$$

Daily exposure to vibration was assessed in terms of 8 h energy equivalent frequency weighted acceleration $A(8)$ in m/s^2 according to the British Standard 6842:

$$A(8) = (T/8)^{0.5} \cdot A(T) \text{ m/s}^2$$

where $A(T)$ is the frequency weighted energy equivalent acceleration for a daily exposure of T h.¹⁸

On the basis of the estimated periods of tool use, a lifetime vibration dose for each stone worker was calculated by a method of summation suggested by Griffin:

$$\text{Lifetime dose} = (\sum (a_{h,w}^2 \cdot t_h)^{0.5} \cdot t_d \cdot t_y)^2 \text{ m}^2 \text{h}^3/\text{s}^4$$

where $a_{h,w}$ is the frequency weighted acceleration measured on the vibrating tools (m/s^2), t_h is the individually estimated daily exposure (h/day), t_d is the number of working days/y, and t_y is the number of years during which the tool was used.¹⁹

STATISTICAL METHODS

Data were analysed with the BMDP/Dynamic software (Release 7.0). Continuous data were summarised as means (SD). The difference between two means was tested by Student's t test and more than two means by one way analysis of variance (ANOVA). The Scheffé method was used for pairwise mean comparisons in ANOVA. The relation between continuous variables was assessed by the method of the least squares. Appropriate transformations of both the response and the explanatory variables used in linear regression analysis were found by the methods suggested by Box and Cox²⁰ and Atkinson.²¹ The χ^2 statistic was applied to data tabulated in 2×2 or $2 \times k$ contingency tables. The association between upper limb disorders and vibration exposure was assessed by multivariate logistic regression analysis. Logistic regression coefficients and standard errors were used to obtain prevalence odds ratios (OR) and 95% confidence intervals (95% CI) adjusted for several potential confounders. Stepwise selection of predictor variables was based on the likelihood ratio χ^2 test. The goodness of fit of the

logistic models was assessed by the Hosmer-Lemeshow χ^2 statistic.²² To test the hypothesis of a monotonic dose-response relation for vibration induced disorders among the exposed stone workers—that is, increasing risk with increasing exposure—polynomial regression analysis was performed with quadratic logistic regression as suggested by Maclure and Greenland.²³ Incremental odds ratios (IOR), adjusted for covariates, were calculated by contrasting the risk for vibration induced disorders at each category of exposure with the risk at only the next lower category. The unexposed category (the controls) was excluded from the quantitative dose response analysis.

Results

TOOL VIBRATION

Table 1 shows the magnitudes of the rms of the frequency weighted and unweighted accelerations measured in the dominant axis of vibration, and the vector sum of vibration accelerations from the power tools used in the quarries and mills. As expected, small differences between the frequency weighted acceleration in the dominant axis and the acceleration vector sum were found for the pneumatic tools of percussive type such as rock breakers, rock drills, and stone hammers. During stone drilling and breaking the frequency weighted acceleration in the dominant axis averaged 15 (5.4) m/s^2 . For the heavy quarry tools, the greatest accelerations were measured in the percussive direction around the 31.5-Hz band. During stone cutting and carving with the small stone hammers operating at full throttle, the frequency weighted acceleration in the percussive axis averaged 21.8 (6.6) m/s^2 . Vibration from these tools showed the highest accelerations at the fundamental frequency of 80 Hz and at the harmonics of 160 and 250 Hz. The mean value of the frequency weighted acceleration measured on the handles of the rotary tools during stone grinding and cutting was 2.84 (1.69)

Table 1 Mean magnitude of root mean square (RMS) of the frequency weighted and unweighted acceleration (6.3–1250 Hz) measured in the dominant axis of vibration and the vector sum of vibration accelerations measured on the handles of portable vibrating tools during quarrying and stonecarving

Tool type	Weight (kg)	Rms acceleration (m/s^2)			
		Weighted		Unweighted	
		Dominant axis	Vector sum	Dominant axis	Vector sum
Rock breaker:					
A	9	10.5	14.3	87.7	100.2
B	27	9.55	10.2	77.5	89.1
C	24	9.89	13.6	83.6	97.6
Rock drill:					
A	16	18.6	19.8	83.0	111.7
B	21	20.9	21.6	114.8	132.1
C	27	19.3	20.2	87.6	110.7
D	12	12.4	14.7	71.9	93.6
E	18	18.2	19.4	83.3	96.3
Stone hammer:					
A	1	21.2	22.6	120.2	140.8
B	1.25	25.1	26.2	131.1	148.2
C	0.5	13.0	13.2	89.2	94.3
D	1.1	19.7	21.1	98.8	128.4
E	1.9	29.9	32.1	138.6	156.7
Angle grinder:					
A	5.5	2.85	4.56	49.5	75.4
B	1.5	1.09	1.71	25.1	36.9
C	4.5	4.92	5.05	33.6	38.0
D	4.8	1.73	2.26	28.8	42.9

Table 2 Characteristics of the controls and the stone workers exposed to hand transmitted vibration

	Controls (n = 258) (n (%))	Stone workers (n = 570) (n (%))
Age (y):		
<30	89 (34.5)	196 (34.4)
30-45	99 (38.4)	148 (26.0)
>45	70 (27.1)	226 (39.6)*
Cigarette smoking (pack-y):		
0	169 (65.5)	329 (57.7)
<10	40 (15.5)	108 (18.9)
>10	49 (19.0)	133 (23.3)
Alcohol (g/day):		
0	77 (29.8)	161 (28.2)
<50	102 (39.5)	254 (44.6)
>50	79 (30.6)	155 (27.2)
Cardiovascular drugs	7 (2.7)	27 (4.7)
Upper limb injuries	62 (24.0)	161 (28.2)
Previous jobs with vibrating tools	0 (0)	22 (3.9)

*p < 0.001 by χ^2 test.

m/s². The greatest vibrations occurred at 100 Hz (fundamental frequency) and at 200 and 400 Hz.

CHARACTERISTICS OF THE WORKER GROUPS

The vibration exposed stone workers were, on average, older than the controls (39.1 v 36.7 y, $P < 0.01$). Between the two groups no difference in other individual characteristics was found (table 2). Seven workers exposed to vibration (1.2%) and three controls (1.1%) had a positive family history for Raynaud like symptoms, but these subjects had no vascular disturbances at the time of the survey. One stone worker was affected with a mild form of asymptomatic non-insulin dependent diabetes. No subjects had disorders of the connective tissues. Medical treatment for cardiovascular diseases (hypertension, ischaemic, or valvar heart diseases) was reported by seven controls (2.7%) and 27 stone workers exposed to vibrations (4.7%, $P = 0.19$). Univariate analysis showed no association between systemic diseases and vibration exposure. According to these findings, systemic diseases were not considered to be important confounders and, as a result, no subjects were excluded from the study.

Among the stone workers who used hand held power tools, vibration exposure in terms of years of tool usage, A(8), and lifetime dose was found to be greater in the quarry drillers and stonecarvers B than in the stonecarvers A

Table 3 Mean (SD) exposures to hand transmitted vibration in the quarry drillers, and the stonecarvers who use only rotary tools (A) or both rotary and percussive tools (B)

	Quarry drillers (n = 145)	Stonecarvers A (n = 188)	Stonecarvers B (n = 237)	Total (n = 570)
Age (y)	40.3 (12.2)	37.9 (11.8)	39.4 (13.7)	39.1 (12.7)
Duration of exposure (y)	18.3 (13.2)	14.9 (10.6)	18.9* (13.6)	17.4 (12.7)
Daily exposure (h)	4.1 (0.8)	4.3 (1.7)	4.9 (0.9)	4.5 (1.2)
Yearly exposure (h/y)	940 (397)	978 (534)	1112** (466)	1024 (479)
A(8)† (m/s ²)	12.4 (3.3)	2.14 (2.0)	10.8** (4.7)	8.37 (5.7)
Lifetime vibration‡ (ln (m ² h/s ⁴))	22.9 (2.1)	18.7 (2.4)	22.6** (2.4)	21.4 (3.0)

F test: *p < 0.01; **p < 0.001.

†A(8) is the frequency weighted energy equivalent acceleration for a period of 8 h.

‡Lifetime vibration is expressed on a logarithmic (ln) scale.

Table 4 Distribution of upper limb disorders among the controls and the stone workers exposed to hand transmitted vibration: the ORs were adjusted for several covariates (age, smoking, alcohol consumption, and upper limb injuries) by logistic modelling

Disorders	Controls (n = 258) (n (%))	Stone workers (n = 570) (n (%))	OR (95% CI)
Sensorineural disturbances	42 (16.3)	228 (40.0)	3.49 (2.36-5.15)
Symptoms of VWF	11 (4.3)	172 (30.2)	9.33 (4.91-17.8)
Signs and symptoms of CTS	6 (2.3)	50 (8.8)	3.43 (1.42-8.28)
Dupuytren's contracture	9 (3.5)	57 (10.0)	2.60 (1.24-5.49)
Muscular weakness	2 (0.8)	39 (6.8)	7.78 (1.84-32.9)
Pain in the upper limbs	45 (17.4)	194 (34.0)	2.27 (1.55-3.33)

VWF = vibration induced white finger; CTS = carpal tunnel syndrome.

(table 3). In the entire vibration group, the mean value of daily exposure time was 4.5 h/day, A(8) was 8.4 m/s², and total duration of exposure was 17.4 y. The length of employment in the stone industry averaged 15.5 y in the control group ($P > 0.1$).

DISORDERS OF HAND-ARM VIBRATION SYNDROME

After adjustment for potential confounders (age, smoking, alcohol consumption, and upper limb injuries), the prevalence odds ratios for the workers exposed to vibration compared with the controls significantly exceeded unity for all the upper limb disorders investigated (table 4). In the vibration group the observed prevalences were 40.0% for SN disturbances (OR = 3.49), 30.2% for VWF (OR = 9.33), 8.8% for signs and symptoms of CTS (OR = 3.43), and 10.0% for Dupuytren's contracture (OR = 2.60). The stone workers exposed to vibration also complained more frequently of muscular weakness and pain in the upper limbs. Significantly increased ORs for most disorders were also

Table 5 Distribution of upper limb disorders among the quarry drillers, and the stonecarvers who use only rotary tools (A) or both rotary and percussive tools (B)

Disorders	Quarry drillers (n = 145)	Stonecarvers A (n = 188)	Stonecarvers B (n = 237)
Sensorineural disturbances:			
No (%)	58 (40.0)	77 (41.0)	93 (39.2)
OR	3.14	3.98	3.36
95% CI	1.92-5.14	2.49-6.34	2.14-5.27
Symptoms of VWF:			
No (%)	59 (40.7)	26 (13.8)	87 (36.7)
OR	15.1	3.43	12.8
95% CI	7.41-30.7	1.62-7.25	6.50-17.25
Signs and symptoms of CTS:			
No (%)	21 (14.5)	14 (7.4)	15 (6.3)
OR	5.59	3.24	2.27
95% CI	2.14-14.6	1.20-8.77	0.84-6.12
Dupuytren's contracture:			
No (%)	16 (11.0)	12 (6.4)	29 (12.2)
OR	2.58	1.85	3.23
95% CI	1.07-6.20	0.74-4.61	1.44-7.23
Muscular weakness:			
No (%)	15 (10.3)	6 (3.2)	18 (7.6)
OR	11.5	3.91	8.68
95% CI	2.53-51.8	0.77-19.8	1.96-38.5
Pain in the upper limbs:			
No (%)	47 (32.4)	62 (33.0)	85 (35.9)
OR	1.96	2.37	2.40
95% CI	1.18-3.23	1.49-3.77	1.54-3.74

Adjustments and abbreviations as for table 4. The controls were assumed to have OR = 1.0.

Table 6 Distribution of sensorineural (SN) symptoms and vibration induced white finger (VWF) by stages in the controls, quarry drillers, and stonecarvers who use only rotary tools (A) or both rotary and percussive tools (B)

Symptom stages	Stone workers				
	Controls (n = 258) (n %)	Quarry drillers (n = 145) (n %)	Stonecarvers A (n = 188) (n %)	Stonecarvers B (n = 237) (n %)	Total (n = 570) (n %)
SN stages:					
SN0	216 (83.7)	87 (60.0)	111 (59.0)	144 (60.8)	342 (60.0)
SN1	33 (12.8)	31 (21.4)	58 (30.9)	52 (21.9)	141 (24.7)
SN2	4 (1.6)	10 (6.9)	10 (5.3)	19 (8.0)	39 (6.8)
SN3	5 (1.9)	17 (11.7)	9 (4.8)	22 (9.3)	48 (8.4)
VWF stages:					
VWF0	247 (95.7)	86 (59.3)	162 (86.2)	150 (63.3)	398 (69.8)
VWF1	8 (3.1)	13 (9.0)	10 (5.3)	12 (5.1)	35 (6.1)
VWF2	2 (0.8)	27 (18.6)	9 (4.8)	32 (13.5)	68 (11.9)
VWF3	1 (0.4)	19 (13.1)	7 (3.7)	43 (18.1)	69 (12.1)

found for each of the job categories exposed to vibration compared with the controls (table 5). The prevalence of VWF was found to be greater among the quarry drillers (40.7%) and the stonecarvers B (36.7%) than among the stonecarvers A (13.8%). With the stonecarvers A as the reference category, the adjusted OR for VWF was 4.40 (95% CI = 2.50–7.74) for the quarry drillers and 3.75 (95% CI = 2.22–6.33) for the stonecarvers B. No significant difference in the occurrence of other disorders was found between the job categories exposed to vibration. The distribution of SN disturbances by stage was similar among the workers exposed to vibration (table 6), whereas moderate or severe symptoms of

VWF (stages 2 and 3) were more frequently found in the quarry drillers and stonecarvers B than in the stonecarvers A ($P < 0.001$). Most of the workers who had VWF experienced blanching attacks in both hands (70.3%). The second, third, and fourth fingers were the most affected ones (18.8%–23.0%). No significant association was found between SN disturbances, signs and symptoms of CTS, and VWF ($P > 0.35$), suggesting that the various components of the hand-arm vibration syndrome may develop independently of each other.^{14 15}

RELATION BETWEEN UPPER LIMB DISORDERS AND VIBRATION EXPOSURE

The occurrence of sensorineural, vascular, and musculoskeletal disorders was also investigated by vibration exposure. Table 7 shows the adjusted ORs for the stone workers exposed to vibration divided into several categories of lifetime dose, when compared with the controls. Significant associations between upper limb disorders and vibration exposure were found, mainly for the stone workers with a cumulative vibration dose $>21.5 \text{ m}^2\text{h}^3/\text{s}^4$ (ln scale). Within the vibration group, however, only VWF showed a pattern of increasing ORs with increasing vibration exposure (table 8). All of the lower 95% CIs for the incremental OR estimates were >1 , providing evidence for an increasing dose-response relation between VWF and vibration exposure. It should be noted that the lowest dose category consisted primarily of stonecarvers who operated only rotary tools generating low magnitudes of hand transmitted vibration. In the exposure-response analysis, we found a continuously increasing risk for VWF with increasing equivalent daily acceleration and duration of tool usage (results not shown).

The log odds of risk of VWF associated with vibration exposure was also estimated with A(8) and duration of exposure as quantitative predictor variables (fig 1). The logistic model including linear terms for each of A(8) and duration of exposure achieved an excellent goodness of fit (Hosmer-Lemeshow $\chi^2 = 2.295$, degrees of freedom = 8, $P = 0.971$). The specific test for curvature in the regression line was not significant ($P = 0.343$ for the quadratic effect of A(8) and $P = 0.149$ for the quadratic effect of duration of exposure). No interaction of A(8) with duration of exposure

Table 7 Distribution of upper limb disorders in the vibration exposed stone workers, divided into categories of lifetime vibration dose (ln scale)

Disorders	Lifetime vibration dose (ln ($\text{m}^2\text{h}^3/\text{s}^4$))			
	<19.5 (n = 145)	19.5–21.5 (n = 157)	21.5–24 (n = 131)	>24 (n = 137)
Sensorineural disturbances:				
No (%)	38 (26.2)	56 (35.78)	50 (38.2)	84 (61.3)
OR	2.91	3.29	3.12	4.69
95% CI	1.70–4.97	2.02–5.36	1.89–5.17	2.81–7.82
Symptoms of VWF:				
No (%)	14 (9.7)	25 (15.9)	46 (35.1)	87 (63.5)
OR	2.70	4.29	11.3	27.3
95% CI	1.17–6.26	2.03–9.08	5.56–23.1	13.1–56.6
Signs and symptoms of CTS:				
No (%)	4 (2.8)	11 (7.0)	16 (12.2)	19 (13.9)
OR	1.85	3.26	5.11	3.24
95% CI	0.50–6.91	1.16–9.19	1.91–13.7	1.21–8.69
Dupuytren's contracture:				
No (%)	6 (4.1)	11 (7.0)	13 (9.9)	27 (19.7)
OR	1.93	2.25	2.57	3.20
95% CI	0.64–5.84	0.88–5.72	1.04–6.36	1.39–7.37
Muscular weakness:				
No (%)	5 (3.4)	2 (1.3)	9 (6.9)	23 (16.8)
OR	6.13	1.60	8.33	14.7
95% CI	1.14–33.0	0.22–11.6	1.75–39.6	3.25–66.6
Pain in the upper limbs:				
No (%)	30 (20.7)	47 (29.9)	41 (31.3)	76 (55.5)
OR	1.75	2.19	2.02	3.15
95% CI	1.01–3.02	1.34–3.56	1.21–3.37	1.91–5.20

Adjustments and abbreviations as for table 5.

Table 8 Dose-response relation for vibration induced white finger among the stone workers, divided into categories of lifetime vibration dose (ln scale): incremental odds ratios (IOR) were obtained by polynomial regression, contrasting the risk at each category of exposure with the risk of the next lower category

	Lifetime vibration dose (ln ($\text{m}^2\text{h}^3/\text{s}^4$))			
	<19.5 (n = 145)	19.5–21.5 (n = 157)	21.5–24 (n = 131)	>24 (n = 137)
OR (95% CI)	1.0	1.60 (0.78–3.28)	4.23 (2.14–8.37)	10.2 (4.81–21.6)
IOR (95% CI)		1.93 (1.07–3.45)	2.10 (1.42–3.10)	2.83 (1.85–4.34)

Adjustments and abbreviations as for table 4. The lowest exposure category was assumed to have OR = 1.0.

Figure 1 Log odds of occurrence of vibration induced white finger (VWF) according to 8 h frequency weighted energy equivalent acceleration ($A(8)$, x_1 in m/s^2) and duration of vibration exposure (x_2 in y), included in the logistic model as quantitative independent variables. On grounds of expediency, 3 has been added to each of the log odds in the graph.

$\ln(P/(1-P)) = -2.954 + 0.09923(x_1) + 0.06302(x_2)$
Goodness of fit χ^2 (Hosmer-Lemeshow) = 2.295, $df = 8$, $P = 0.971$

Figure 2 Expected occurrence of vibration induced white finger (VWF) among the stone workers operating vibrating tools, as estimated by regression of the log (ln) transformed VWF prevalence (y) on log $A(8)$ (8 h frequency weighted energy equivalent acceleration, x_1 in m/s^2) and log duration of vibration exposure (x_2 in y): $\ln y = 1.0266 + 0.4747(\ln x_1) + 0.535(\ln x_2)$. The regression equation was approximated to: $y = 2.79156 \cdot (x_1)^{1/2} \cdot (x_2)^{1/2}$.

was found. Hence, the results of the quantitative logistic analysis suggested that the effects of $A(8)$ and duration of exposure combined to increase the risk for VWF among the stone workers exposed to vibration. In particular, the OR for VWF was estimated to increase by 1.10 (95% CI = 1.06–1.15) for each unit of daily vibration exposure (m/s^2) and by 1.07 (95% CI = 1.05–1.08) for every unit of exposure duration (y). It is also remarkable that the baseline probability of white finger predicted by the logistic model was 0.049, a figure very similar to that found among the controls (4.3%).

RISK ASSESSMENT FOR VWF AMONG THE STONeworkERS

For purposes of comparison with the dose effect guidances included in the annexes to some Standards,^{17,18} the observed prevalence of VWF was related to the midpoints of several intervals of $A(8)$ and duration of exposure. Tests for data transformations suggested a linear model in which the $\ln$ transformed prevalence of VWF was regressed on $\ln A(8)$ and $\ln$ duration of exposure (adjusted $R^2 = 0.908$, fig 2 and table 9). According to the exposure data of this study, the estimated regression equation indicates that the expected percentage of stone workers affected with VWF tends to increase roughly in proportion to the square root of $A(8)$ (for a par-

ticular exposure period) or in proportion to the square root of the duration of exposure (for a vibration of constant magnitude). This relation was confirmed by that found between VWF and lifetime vibration dose (fig 3). On grouping the stone workers into increasing intervals of cumulative dose, the expected occurrence of VWF was found to be proportional to a power of the lifetime dose (dose^{1/4}, adjusted $R^2 = 0.971$).

Discussion

VALIDITY OF THE STUDY AND COMPARISON WITH OTHER INVESTIGATIONS

In this study of stone workers exposed to hand transmitted vibration, the overall prevalence of VWF was found to be 30% and sensorineural symptoms 40%. These figures are quite similar to those reported by most of the authors who investigated the occurrence of vibration induced disorders in the stone industry (table 10). The very high prevalence

Table 9 Expected prevalence of vibration induced white finger (%) among the stone workers according to the estimated 8 h frequency weighted energy equivalent acceleration ($A(8)$ in m/s^2) and the duration of exposure: (figure 2 shows the estimated regression equation)

$A(8)$ (m/s^2)	Duration of exposure (y)						
	1	2.5	5	10	15	20	30
1	2.8	4.4	6.2	8.8	10.8	12.5	15.3
2.5	4.4	7.0	9.9	14.0	17.1	19.7	24.2
5	6.2	9.9	14.0	19.7	24.2	27.9	34.2
10	8.8	14.0	19.7	27.9	34.2	39.5	48.3
15	10.8	17.1	24.2	34.2	41.9	48.3	59.2

Figure 3 Relation between the prevalence of vibration induced white finger (VWF) and the estimated lifetime vibration dose in the stone workers who use vibrating tools.

Table 10 Observed prevalence of vibration induced white finger (VWF) and sensorineural (SN) symptoms in reports of epidemiological studies of stone workers exposed to hand transmitted vibration

Author(s)	Sample (n)	VWF	SN symptoms
		(N(%))	(N(%))
Loriga ¹ (1911)	≈200	—	40 (20.0)
Edsall ¹ (1918)	19	19 (100)	—
Hamilton ² (1918)	38	34 (89.5)	—
	50	43 (86.0)	—
	78	44 (56.4)	—
Takamatsu (1973)**	58	24 (42.0)	38 (66.0)
Osaki (1974)**	61	21 (34.4)	12 (19.7)
Iwata (1975)**	90	40 (44.4)	—
Miura ³ (1975)	70	26 (37.1)	24 (34.3)
Miura (1976)**	71	28 (39.4)	28 (40.1)
Nakaya (1978)**	314	64 (20.1)	—
Färkkilä <i>et al.</i> ⁴ (1978)	16	14 (87.5)	—
Olsen and Nielsen ⁵ (1979)	18	13 (72.0)	—
Kuzalová <i>et al.</i> ⁶ (1984)	174	90 (52.0)	—
Taylor <i>et al.</i> ⁷ (1984)	30	19 (63.3)	11 (30.0)
Sakakibara <i>et al.</i> ⁸ (1984)	69	25 (36.2)	—
Futatsuka <i>et al.</i> ⁹ (1985)	42	13 (31.0)	23 (54.8)
Bovenzi <i>et al.</i> ¹⁰ (1988)	76	27 (35.5)	31 (40.8)
Tominaga ¹² (1992)	69	20 (29.0)	25 (36.2)
Present study (1993)	570	172 (30.2)	228 (40.0)

*Cited by Griffin¹¹.

**Cited by Takamatsu *et al.*⁶

of VWF found in the studies performed from 1910–1920 (56%–100%) is probably due to an excessive daily tool use (from 7–10 h/day according to Loriga¹ and Hamilton²). Discrepancies with the results of other surveys may also depend on differences in the study design and the sample sizes, which in general were much smaller than that of our study. It is well known that prevalence studies are suitable for investigating occupational diseases persisting for long periods of time, but they can have various limitations. On planning this study several efforts were made to control potential sources of bias. From the registers of the companies it seemed that by 1975 the level of employment was stable in the quarries and mills investigated in this study. This information, however, cannot exclude selection bias due to work force turnover, as only actively employed workers were investigated. Nevertheless, according to employers' appraisal there was little job mobility in the last 15 years, during which time stone production in Italy increased more than 10%. Likewise, changes in job categories within the industry were negligible, as stone processing requires skilled labour. Furthermore, the finding of an increasing occurrence of upper limb disorders with increasing age for both the workers exposed to vibration and the controls (test for linear trend: $P < 0.001$), as well as the use of an internal comparison group with similar socioeconomic characteristics, suggest that bias due to the healthy worker effect was, at least partially, minimised. All the active stone workers participated in the survey, so that self selection was not a source of bias in this study. Data on current exposure to vibration was considered a reliable surrogate for past exposure as the type and design of most vibrating tools had remained fairly similar over time.^{7–10} In this investigation, subjects' daily exposure time and total years of tool use were estimated on the basis of information obtained by interviewing employees and employers and by consulting personnel

employment records, when available. Certainly, daily and lifetime exposures may be subject to recall bias. Nevertheless, there is some evidence for a good concordance between estimated and measured exposure time among workers exposed to vibration.²⁴ In this study the occurrence of vibration induced disorders was investigated by assessment questionnaires and the Stockholm workshop scales were used to grade sensorineural and vascular symptoms. We recognise that symptoms reported by patients may be open to bias. Nevertheless, in view of the large population studied the use of assessment questionnaires, based on international symptom scales and given by trained occupational physicians, may be considered appropriate to investigate the occurrence of vibration induced disorders among worker groups at risk.

NON-VASCULAR DISORDERS

The findings of our study showed that the prevalence of upper limb disorders was significantly greater among the stone workers exposed to vibration than among the controls who performed only manual work. The occurrence of sensorineural disturbances tended to increase with increasing exposure to vibration, but a linear dose-response relation could not be shown. It may be argued that the sensorineural scale adopted in this study is not fully adequate to discover an effect of exposure and this limitation may be responsible for the lack of significant findings. For other disorders including CTS, Dupuytren's contracture, muscle weakness, and pain in the upper extremities, trend statistics did not show an increasing risk with increasing lifetime dose of vibration. It is likely that as well as vibration, several other stress factors can contribute to the onset and development of musculoskeletal disorders. Working with vibrating tools during quarrying and stone processing involves not only vibration exposure, but also awkward postures, firm hand grip on tool handles, forceful and sometimes repetitive movements which can overload the muscles, tendons, and bones of the upper limbs. From a medicolegal point of view, it is worth noting that a recent recommendation of the Commission of the European Communities (EC) includes the disorders due to overstraining of the tendon sheaths, the peritendinous tissues, and the muscular and tendinous insertions, in a list of diseases recognised to be linked directly to the occupation.²⁵ According to the EC Commission, the Member States should consider these occupational diseases liable for compensation and subject to preventive measures.

DOSE-RESPONSE RELATION FOR VWF

The association between VWF and occupational exposure to hand transmitted vibration is well recognised, but the form of the exposure-response relationship for VWF is not yet fully understood.^{11–26} In this study, symptoms of VWF were found to be associated with several indicators of exposure to vibration such as equivalent daily acceleration, total

exposure duration, and lifetime dose. Furthermore, within the group exposed to vibration there was evidence that the risk for VWF continued to increase with each increment of vibration exposure, suggesting a monotonic dose-response relation.

Annex A to ISO 5349¹⁷ proposes a dose-effect relation between the energy equivalent frequency weighted acceleration for a period of four hours—that is, $A(4) = A(8) \cdot \sqrt{2}$ —and the duration of exposure necessary before the onset of VWF—that is, the latency for finger blanching. On the basis of the observed VWF prevalence and the estimated $A(4)$ for the stone workers of this study, the ISO equation predicted latent periods of 3.44 years for the quarry drillers, 11.6 years for the stonecarvers A, and 3.76 years for the stonecarvers B. The observed mean latencies for VWF were 16.5 years for quarry drillers, 12.7 years for stonecarvers A, and 16.1 years for stonecarvers B. These findings indicate a good agreement between the expected and observed latencies for the stonecarvers operating only rotary tools, and an overestimation of risk of VWF for the stone workers exposed to vibration from percussive tools. The tendency of ISO 5349 to overestimate the risk in some categories of workers exposed to vibration has been reported by several investigators.^{10 27–29} It may be argued that the dose-effect guidance offered by ISO 5349 estimates correctly the risk for worker groups exposed to vibration from specific types of tools—for example, grinders, chain saws—whereas it is not applicable to all other sources of hand transmitted vibration. For instance, it has been suggested that the ISO frequency weighting factors may be inappropriate for hand held tools generating vibrations with dominant low frequencies.

A substantial difference between the dose-effect relation suggested by ISO 5349 and that estimated in the present survey arises from the definition of exposure duration. In the standard the mean duration of exposure represents the mean latent period required before VWF symptoms develop in selected percentiles of a group exposed to vibration. But, as discussed by Griffin, within a population group the mean latency for the individuals affected with VWF is always shorter than the mean vibration exposure period for the group members, and this leads to overestimate the risk for VWF with respect to the vibration exposure (magnitude and duration) experienced by the entire worker group.¹¹ In our study, the dose-response relation for VWF among the stone workers exposed to vibration could be approximated by a relation in which a twofold change in the percentage of workers affected results from a fourfold change in $A(8)$ (for the same number of years of exposure) or from a fourfold change in exposure duration (for a constant magnitude of equivalent daily vibration). In contrast, the ISO dose-effect relation predicts a fourfold increase in occurrence of VWF for a twofold increase in four hours energy equivalent acceleration (with the latent period unchanged). As suggested by some investigators, dose-response relations

based on the mean latency as an indicator of exposure duration tend to allow greater prevalences of VWF with lower vibration magnitudes.^{11 26} Hence, it is not surprising that the use of different quantities to express exposure duration (latency or total exposure period) can result in discrepancies between studies in the risk estimates for VWF.

It is recognised that the prevalence of symptoms of VWF in a group exposed to vibration depends on several factors including the characteristics of vibration exposure (magnitude, frequency, duration), the operator's method of working, the environmental conditions, and the individual susceptibility. Prevalence, as an effect measure, is also highly dependent on the rate at which workers enter and leave the group. Even though the relation of VWF to vibration exposure has proved to be complex and the results of cross sectional surveys should be interpreted with caution, nevertheless the findings of this study suggest a simple dose-response relation based on a time dependency such that, if vibration magnitudes are doubled, a halving of the years of exposure is required to produce the same effect. Thus, within the frame of the currently proposed time dependencies for vibration exposure, this study tends to substantiate a form of dose-response relation in which vibration magnitude and total duration of exposure contribute equally to the prediction of occurrence of VWF. This finding provides epidemiological support to some general statements contained in hand transmitted vibration standards^{17 18} and adds further dose-effect information for future development of the current standards. Even though limited to a specific category of workers exposed to vibration our results may also be used to assist in the formulation of exposure limits. With regard to this subject, the EC Commission has recently suggested exposure levels for hand transmitted vibration within a proposal of directive for the protection of workers from the risks arising from physical agents.³⁰ In the proposal of directive the methods of measurement and assessment of vibration exposure are basically derived from BS 6842,¹⁸ and the exposure levels are expressed in terms of $A(8)$. The threshold level is established at 1 m/s^2 , the action level at 2.5 m/s^2 , and the ceiling level at 5 m/s^2 . Specific provisions are indicated for exposure values above the threshold level, which is defined as "the value towards which implementation of this Directive should be geared". Considering a prevalence of 10% as a threshold effect value for VWF in a group exposed to vibration,¹⁸ the dose-response relation of this study predicts that such a prevalence will occur after about 5.1 years of exposure to the EC action level. This figure is similar to that suggested in a recent review paper,³¹ and is not far from the estimates provided by BS 6842.¹⁸

Conclusion

The findings of this study showed a greater occurrence of upper limb disorders in quarry drillers and stonecarvers exposed to vibration

than in control stone workers performing only manual activity. As well as vibration, ergonomic stress factors are likely to have played a part in the development of carpal tunnel syndrome and musculoskeletal disorders among the stone workers who use hand held vibrating tools. Symptoms of VWF were strongly related to vibration exposure, and a monotonic dose-response relation could be shown. Even though the results of this study concern the health hazards associated with the use of vibratory tools in a specific work situation, nevertheless the estimated relation between VWF and exposure to vibration was found to be consistent with the current state of knowledge of the dose-effect relation for hand transmitted vibration.¹⁷ Differences in the estimates of the expected occurrence of VWF between different studies are probably due to several factors such as the variability in dose-response data that arise from different jobs and exposure conditions, the use of non-uniform methods for the assessment of daily and cumulative exposure to vibration, and some general limitations related to the design of occupational cross sectional studies. Our findings and the results of other epidemiological studies seem to indicate that the vibration acceleration levels currently under discussion within the EC represent reasonable exposure limits for the protection of workers against the harmful effects of hand transmitted vibration.³² The adoption of the proposed vibration limits, together with the implementation of the administrative, technical, and medical measures specified in the EC directive for physical agents,³⁰ should contribute to decrease the risk of disorders induced by vibration among the exposed workers.

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