Int Arch Occup Environ Health (1998) 71: 270–276

ORIGINAL ARTICLE

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Neurological and functional effects of short-term exposure to hand-arm vibration

Received : 7 April 1997 / Accepted: 25 September 1997

Abstract ***Objective:*** The aim of the present study was to quantify the sensory and functional effects resulting from a short-duration (30 min) exposure to hand-arm vibration. ***Subjects and methods:*** Nine subjects went through nine laboratory experiments. For 32 min they grasped a handle vibrating at three different amplitudes (5, 20, and 80 ms^{-2}) and at three frequencies (31.5, 125, and 500 Hz). Additionally, a reference experiment was conducted in which the handle did not vibrate. Three sensory tests [vibration perception threshold (VPT), pressure perception threshold (PPT), and distal sensory latency time (DSL)], two functional tests [Purdue pegboard (PPB) and maximal voluntary force (MVF)], and a questionnaire concerning the perceived paresthesia and numbness were completed before, during, and after exposure. ***Results:*** A 32-min period of exposure to vibration leads to a temporary threshold shift (TTS) of the VPT and to the development of paresthesia and numbness. The VPT appears to vary with the exposure duration according to a first-order model with a time constant about equal to 3 min. The TTS increases with the vibration acceleration amplitude and is greater for an exposure frequency of 125 Hz than for that of 31.5 or 500 Hz. It is also greater at the test frequency 125 Hz than at 31.5 Hz. The other tests do not demonstrate any significant variation. In particular, the PPB test does not demonstrate any loss of dexterity. ***Conclusion:*** After some 30 min of exposure to vibration the VPTs are increased and paresthesia and numbness develop. However, these do not appear to influence significantly the capacity or performance at work.

Key words Vibration perception threshold · Dexterity · Work performance

Introduction

Many authors have demonstrated temporary alterations in the sensitivity of mechanoreceptors following exposure of the hand to vibration (Lidström et al. 1982; Lundström 1986; Lundborg et al. 1992; Lundström et al. 1992; Maeda and Griffin 1994). These are also known to be associated with paresthesia and numbness (Bovenzi et al. 1980; Takamatsu et al. 1982).

The question remains whether these temporary modifications might have an influence on the dexterity and, eventually, the safety of the workers. Brammer et al. (1987) and Bovenzi (1990) have suggested that manipulative dexterity depends on the functional capacity of the skin mechanoreceptors, which itself can be estimated by the vibration perception threshold (VPT) test. Thonnard et al. (1997) recorded the VPT and the coordination of forces during a prehension test as proposed by Johansson et al. (1980) following a 32-min period of exposure to 100 ms^{-2} at 160 Hz. Although the VPT increased drastically by more than 33 dB on average, the results of the prehension test remained unchanged. This finding is in accordance with the observations made by Hammarskjöld et al. (1991) in carpenters after 10 min of exposure to vibration at 20 ms^{-2}, and 50 Hz; performances in simple tasks such as screwing, nailing, and wood sawing remained unchanged.

These two studies involve, in the first case, a very simple task of lifting a 2 N object between the thumb and the index finger and, in the second case, gross activities that do not involve much tactile sensibility.

Additional research therefore appears necessary to test the dexterity in fine manipulative tasks involving tactile discrimination following exposure to vibration. The purpose of the present research was to investigate this aspect at different levels and frequencies such that

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the sensitivity of different mechanoreceptors be altered. A secondary objective was to verify whether vibration at the same weighted amplitude according to ISO 5349 (1986) but at different frequencies would have the same impact on the sensitivity of the mechanoreceptors.

Subjects and methods

Nine men without any history of peripheral or central neuropathy or of upper limb disorders and who had never been exposed to vibration agreed to participate in the study; their age ranged from 25 to 35 years. They were exposed to ten conditions, i.e., 5, 20, and 80 ms^{-2} (unweighted) at 31.5 (conditions 1–3), 125 (conditions 4–6), and 500 Hz (conditions 7–9), plus a reference condition (numbered 0) without vibration. The vibration was generated using a Tektronix TM 503 frequency generator connected to a Brüel and Kjaer 4808 shaker via a Harfield 2U600 MDS-FET power amplifier. A vertical handle weighing 2 N was mounted on the shaker and was grasped by the subject, the axis of vibration therefore being the axis Y as defined in ISO 5349. The handle was thermoregulated at a temperature of 32°C and was equipped with a strain gauge enabling monitoring of the grip force. This force was displayed in front of the subject, who was advised to keep it at around 20 N. The shaker was counterbalanced and mounted vertically near its center of gravity such that the lifting force and torque were about nil. The posture of the subjects was standardized; they were sitting with the arm along the trunk, with the forearm bent at 90° and resting on a soft support adjusted in height, and with the hand in pronosupination. Five sensory and functional tests were performed on the right hand as follows:

1. The vibration perception threshold test (VPT) was conducted at 31.5 and 125 Hz using a B & K 4810 minishaker mounted on a balance such that the force on the pulp of the test finger (the second finger) was kept constant at 0.2 N. A rod was mounted on the shaker such that the contact surface with the pulp of the finger was 5 mm^2. The signal was generated by a modified audiometer (Madsen Micromate 304) using increments of 5 dB and an ordinary amplifier. The system has a dynamic range of 50–160 dB (ref $10^{-6}\ \mathrm{ms}^{-2}$); (0.3 mms^{-2}– 100 ms^{-2}). The testing procedure was the one used in manual audiometry, with the level being increased progressively until the subject reacted and then being decreased and increased again such that the threshold be crossed three times. The value recorded was the threshold detected three times consecutively.
2. The pressure perception threshold test (PPT) was carried out using the monofilaments of Semmes-Weinstein according to the procedure described by Bell-Krotoski (1990). The recorded value was the number of the filament felt three times consecutively.
3. The nerve conduction test was recorded through the distal sensory latency (DSL) of the median nerve between the wrist and the second finger by means of a Nervepace S200 device (Neurotron Medical; Durnil et al. 1993).
4. The maximal voluntary grip force (MVF) was recorded using a JAMAR PC5031J1 dynamometer. The same posture used during the exposure to vibration was adopted and the recorded value was the maximal force held during a 3-s period.
5. The Purdue pegboard test (PPB) was chosen to test the manual dexterity (Tiffin and Asher 1948; Banister and Smith 1972). The subject had to place as many pegs as possible in the holes of the board within 30 s.

Finally, a questionnaire was used to collect the opinion of the subjects concerning paresthesia and numbness on a scale ranging from 0 (none) to 6 (very strong).

Each experiment lasted about 90 min. All the tests were performed three times (except for DSL, which was performed only once) before the exposure to vibration. The ten exposure conditions were randomized, with each person performing five experiments in the morning and five in the afternoon. A period of at least 24 h separated two consecutive experiments. The exposure to vibration lasted 32 min but was interrupted as briefly as possible (about 60 s) at times 2, 4, 8, and 16 min for the performance of several tests.

Table 1 gives the details of the protocol. The VPT test was performed at each occasion as it varies considerably with the exposure to vibration. In contrast, the DSL test was performed only twice, as preliminary experiments had shown that the results did not vary much and because it was very uncomfortable for the subject. The time at which each test was performed was recorded to the nearest second.

The VPT data were analyzed using the first-order model and the algorithm developed by Malchaire et al. (1998), assuming constant values for the time constant and the residual fraction for each subject. For each experiment the results were expressed in terms of VPT_0 (the threshold before exposure), TTS (the temporary threshold shift of the VPT at steady-state following the exposure to vibration), τ (the time constant for the development and recovery of the TTS), and r (the residual fraction of TTS after 15 min of recovery).

The same analysis was performed on the subjective data concerning paresthesia with the derivation of $\mathrm{TTS}_{\mathrm{par}}$ [the steady-state level of paresthesia complaint on a scale ranging from 0 (no paresthesia) to 6 (very severe paresthesia)] and τ (the time constant for both the development and the recovery of these symptoms).

For these parameters a two-way analysis of variance was performed using the subjects and the exposure conditions (from 0 to 9) as factors. The significance of the differences found between the ten exposure conditions was analyzed using the least-squares difference method. The results of the other tests were also analyzed by multiple analyses of variance using the subjects, the exposure conditions, and the moments of measurements as factors.

Results

Figure 1 shows the evolution of the VPT recorded at 31.5 Hz as a function of time for the ten exposure conditions (mean values for the nine subjects). Fig. 2 provides the same data for paresthesia.

The analyses of variance showed that the time constant for the increase and the recovery of the VPT varied

Table 1 Details of the protocol (*VPT* Vibration perception threshold, *PPT* pressure perception threshold, *DSL* distal sensory latency of the median nerve, *MVF* maximal voluntary force, *PPB* Purdue pegboard)

Before exposure: 3 VPT, 3 PPT, 3 PPB, 1 DSL, 3 MVF, and 1 questionnaire
After 2 min of vibration: 1 VPT + questionnaire
After 4 min of vibration: 1 VPT + 1 PPT
After 8 min of vibration: 1 VPT + questionnaire
After 16 min of vibration: 1 VPT + 1 PPT

After 32 min of vibration at the end of the exposure: VPT, PPT, PPB, DSL, MVF, and questionnaire
After 3 min of recovery: VPT, PPT, + questionnaire
After 6 min of recovery: VPT, PPT, PPB, + questionnaire
After 10 min of recovery: VPT, PPT, + questionnaire
After 15 min of recovery: VPT, PPT, PPB, MVF, + questionnaire

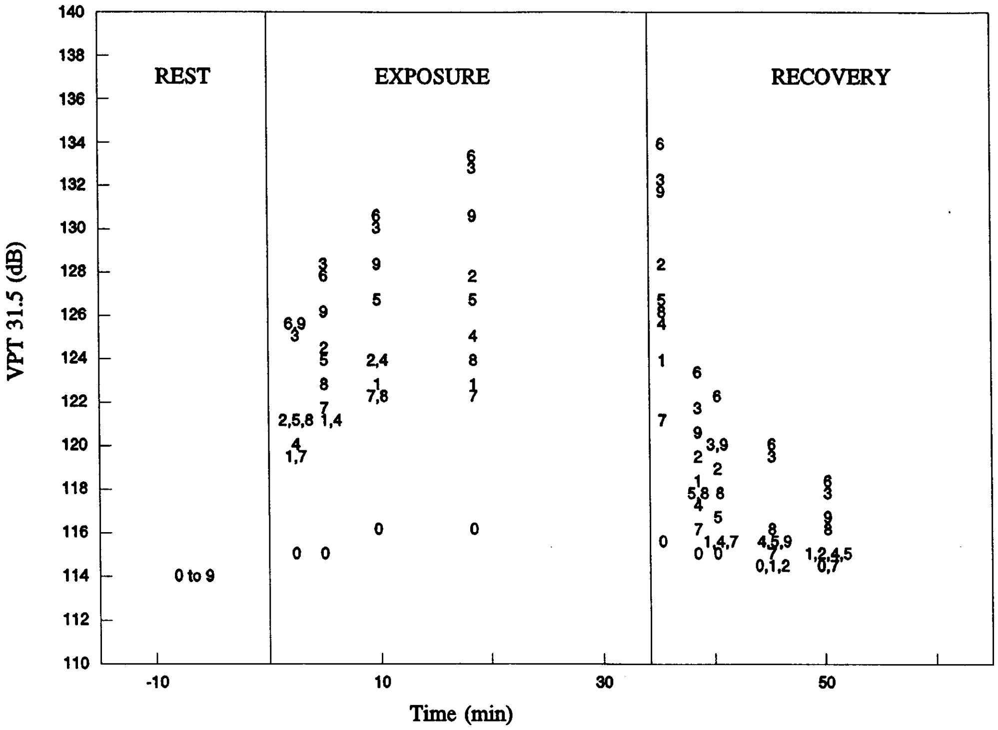

Fig. 1 Evolution of the VPT at the test frequency 31.5 Hz, plotted as a function of time for the 10 exposure conditions numbered from *0* to *9* (the position of the number indicates the mean VPT value recorded for the 9 subjects at different times during the experiments)

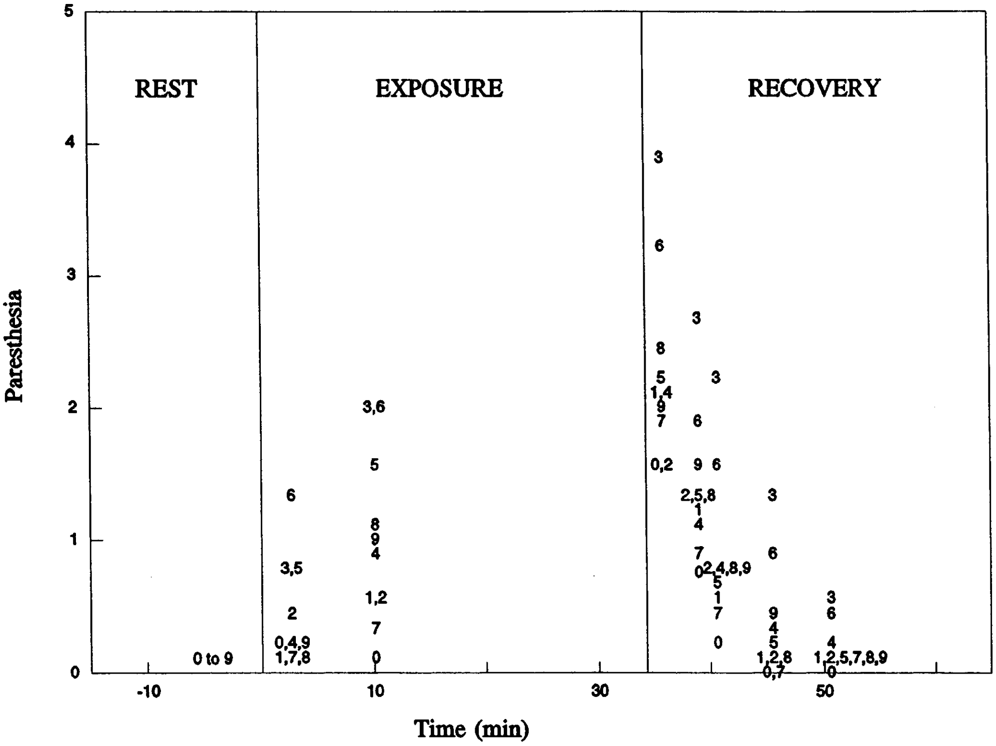

Fig. 2 Evolution of the paresthesia score as a function of time for the 10 exposure conditions numbered from *0* to *9* (the position of the number indicates the mean value of the votes of the 9 subjects as recorded at different times during the experiments)

significantly among the subjects, with mean values (and standard deviations) being 2.6 (±0.5) and 3.2 (±0.4) for the test frequencies 31.5 and 125 Hz, respectively. Similarly, the residual fraction of the TTS was 0.14 (±0.06) for the test frequency 31.5 Hz and 0.07 (±0.04) for the test frequency 125 Hz.

The TTS of the VPT varied considerably between the nine conditions with vibration as shown in Table 2 and illustrated in Fig. 3. The VPT_0 values remained independent of the exposure conditions and were on average 113.5 ± 2.3 dB at the test frequency 31.5 Hz and 96.6 ± 3.2 dB at 125 Hz. The TTS appeared to obey

Table 2 TTS values recorded for the VPT and the symptoms of paresthesia under the 10 exposure conditions. (Data represent mean values ± SD (in parentheses) for the 9 subjects

Exposure condition	Exposure frequency (Hz)	Exposure acceleration (ms^{-2})	TTS, VPT at 31.5 Hz (dB)	TTS, VPT at 125 Hz (dB)	TTS_{par}
0	–	0	0	0	2.2 (0.6)
1	31.5	5	10.5 (3.0)	13.4 (4.1)	3.6 (0.9)
2	31.5	20	16.0 (3.2)	20.9 (5.0)	2.8 (0.8)
3	31.5	80	21.6 (5.3)	30.8 (5.0)	5.1 (1.0)
4	125	5	13.3 (4.3)	17.9 (3.8)	3.0 (1.5)
5	125	20	17.5 (3.6)	26.5 (5.1)	3.7 (0.8)
6	125	80	22.1 (4.1)	37.8 (5.1)	4.5 (1.1)
7	500	5	11.7 (3.7)	14.4 (4.6)	2.5 (0.5)
8	500	20	13.6 (3.5)	20.5 (5.2)	3.5 (1.0)
9	500	80	19.8 (3.0)	27.5 (6.3)	3.3 (1.8)

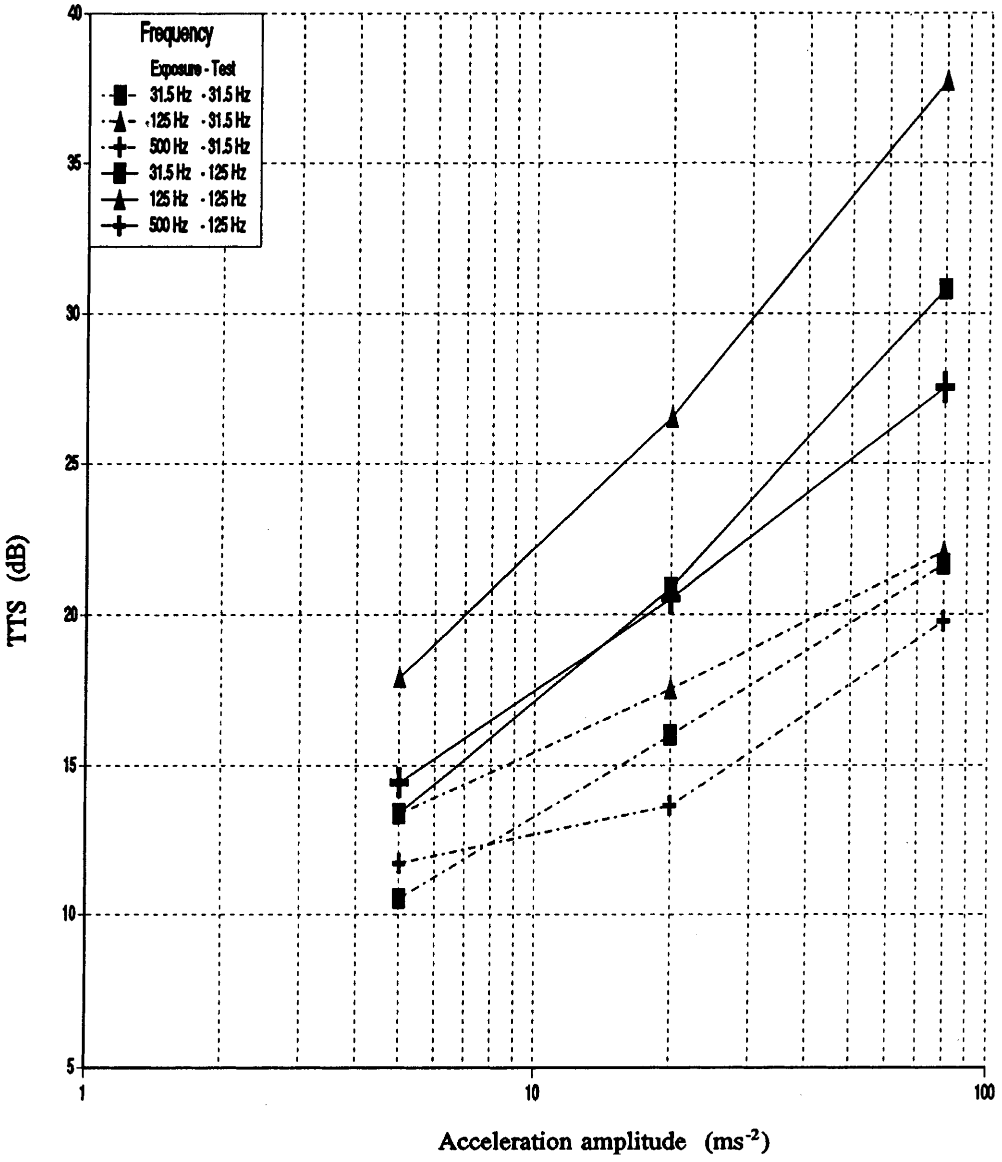

Fig. 3 Evolution of the TTS as a function of the amplitude of acceleration at the 3 exposure frequencies and for the 2 test frequencies

approximately a linear function of the logarithm of the acceleration according to the equations

$$TTS_{31.5} = 103.4 - 0.86\ VPT_0 + 8.3 \log a \quad (R = 0.804)$$

and

$$TTS_{125} = 47.1 - 0.46\ VPT_0 + 14.5 \log a \quad (R = 0.848),$$

where VPT_0 is the VPT before the exposure (in decibels) and a is the exposure acceleration amplitude (in milliseconds^{-2}), when systematic increases of 1.8 and 6.3 dB, respectively, were taken into account for the exposure frequency of 125 Hz as compared with the other two frequencies.

With regard to the symptoms of paresthesia, the results showed large interindividual differences and a slight increase as a function of the acceleration amplitude, regardless of the frequency, according to the equation

$$\mathrm{TTS}_{\mathrm{par}} = 2.9 + 0.018\ a.$$

The correlation coefficient ($R = 0.430$), although statistically significant due to the great number of experiments and degrees of freedom, showed a rather poor relationship. The intercept of this relation (2.9) was about equal to the $\mathrm{TTS}_{\mathrm{par}}$ observed in the reference condition (2.2) due simply to the holding of the handle of the shaker. The time constant was on average 8.3 ± 1.1 min and was therefore longer than that noted for the VPT.

The results of the other tests did not follow the same mathematical model and were therefore analyzed by taking into account the moments of the measurement. The analysis of variance demonstrated very significant differences between subjects ($P < 0.001$) for each test. The results in terms of the differences found between exposure conditions showed considerable contrast.

The PPT increased on average by 2 monofilaments during the experiments conducted at 31.5 Hz and at 20 and 80 ms^{-2} and by 1 filament in all other experiments as compared with the reference condition without vibration. These variations are very small and do not demonstrate a significant alteration in the perception of the pressure according to the scale proposed by Bell-Krotoski (1990). The same conclusion must be drawn for the DSL, which varied slightly but not significantly from 2.12 to 2.55 ms at random between subjects and conditions.

The MVF decreased significantly at the end of the exposure in all experiments, including the reference one. The decrease observed immediately after exposure was on average 40 N, that is, some 8% of the mean MVF, and varied between 27 and 78 N. When the variation in the reference condition was taken into account, it appeared that there was no additional effect of the vibration exposure conditions. The preexposure value was recovered after 15 min.

The results of the PPB tests performed before the exposure to vibration demonstrated a great inter- and intraindividual variability, involving a minimum of 11 pegs and a maximum of 23 pegs, in spite of the training systematically provided at the beginning of the experimental campaign. The paired comparison of the scores before and after exposure to vibration showed that the performances were not statistically significantly influenced by the exposure conditions and remained on the order of 17 pegs in 30 s.

The sensation of numbness also increased significantly in all experiments, including condition 0, to reach a maximum of 3 on the scale of 0 to 6. No effect of vibration exposure could be demonstrated in addition to the effect of holding the handle on the shaker (reference condition), and this sensation disappeared in all subjects after 15 min.

Discussion

The present study was innovative in several aspects as compared with similar studies thus far reported in the literature. The main innovation was the study of VPT evolution during the exposure to vibration and during the recovery period under constant conditions of grip force, pressure force, and hand temperature. A new algorithm was used (Malchaire et al. 1998) to derive the TTS at steady state. Therefore, the results cannot be strictly compared with those reported in the literature, which were simply logarithmically extrapolated from thresholds recorded during the recovery period after periods of exposure to vibration that were too short (3–10 min) for a steady-state condition to be reached. This invalidates the relationships found by these authors between TTS and the frequencies and amplitudes of the vibration exposure. The TTS values are indeed greater than those reported by Harada and Griffin (1991) and Maeda and Griffin (1993). The time constant values, however, are on the same order (2.6 and 3.2 min at 31.5 and 125 Hz respectively), as those reported by Nishiyama and Watanabe in 1981 (5 min) and by Nishiyama et al. in 1994 (2.5 min).

The correlation analysis showed that at the test frequency 31.5 Hz the TTS was systematically 1.8 dB lower for exposure to vibration at 31.5 and 500 Hz as compared with 125 Hz. As the TTS increased as (8.3 log *a*), this means that exposure to an acceleration amplitude 1.6 orders of magnitude greater, or 4.3 dB, is needed at these two frequencies to produce the same TTS that was recorded at 125 Hz.

Similarly, for the test frequency 125 Hz the systematic difference was 6.3 dB and the TTS increased as (14.5 log *a*). The amplitude leading to the same TTS must then be 2.7 times, or 8.7 dB, greater. This weighting is far from the frequency weighting proposed in ISO 5349, according to which the amplitudes should be 4 times smaller at 31.5 Hz and 4 times greater at 500 Hz (−12 and + 12 dB, respectively).

It can therefore be concluded that with regard to the VPT and, therefore, to the sensitivity of the mechanoreceptors and the development of temporary neurological impairment, the ISO frequency weighting has some value above 125 Hz but not at 31.5 Hz. The shape of the ISO weighting curve in the low-frequency range, however, was determined on the basis of the biodynamic considerations, taking into account the resonances of the hand-arm system.

The validity of the results is limited to the experimental conditions. Indeed, it remains to be demonstrated that the time constant as well as the steady-state TTS are independent of the exposure duration.

The DSL did not statistically significantly differ after versus before vibration exposure. This suggests that even following a short-term exposure to vibration, the integrity of the peripheral nerves remains unaffected. It remains to be seen whether such short-term exposure can aggravate the situation for subjects with permanent impairment following a long-term exposure to vibration (Brammer et al. 1987).

Our results confirm the findings by Färkkila et al. (1978, 1980) of no decrease in MVF following a short exposure to vibration among subjects without vibration-induced disorders. This, again, has to be differentiated from the findings by the same authors (Färkkila et al. 1986) of a decrease in MVF in subjects with vibration-induced vascular diseases after 2 years of work with vibrating tools.

The results are the same concerning manual dexterity, at least as tested using the PPB test. However, although the number of pins placed within 30 s remained the same, the subjects clearly experienced some difficulties in picking up an individual pin from the cup. A test for quantification of this effect does not appear to be available. The relevancy of this interference also remains to be demonstrated in the industrial setting. It is also very unlikely that workers from whom such dexterity would be required would be exposed to vibration amplitudes such as those used in the present study.

Paresthesia and numbness were clearly the main effects recognized by the subjects and those of which they complained. Whereas the numbness symptoms and the major part of the paresthesia were due to the grasping of the tool, the paresthesia symptoms increased with the amplitude of vibration. The time constant of the phenomenon was about 8 min, meaning that more than 20 min are needed for the subjects to recover substantially. In many industrial settings, it can therefore be expected that workers constantly endure this type of problem.

The experimental conditions are also different from real working conditions in that the prehension and lifting forces as well as the torque on the handle and the hand temperatures were controlled and in that the exposure vibration was monoaxial and delivered at a single frequency. However, under these conditions, which can be considered as varying from light (5 ms^{-2}) to severe (80 ms^{-2}), the following conclusions can be drawn:

1. The TTS is smaller when the initial VPT_0 value is greater.
2. The VPT at 125 Hz, which reflects the sensitivity of the FA II mechanoreceptors (Pacini corpuscles), is strongly affected and the TTS is strongly dependent on the exposure acceleration amplitude and frequency.
3. The VPT at 31.5 Hz, mainly reflecting the sensitivity of the FA I mechanoreceptors (Meissner corpuscles), is also increased, albeit to a much lesser degree than at 125 Hz.
4. The PPT and DSL sensory tests are not significantly altered. The PPT reflects the sensitivity of the Meissner corpuscles (Bell-Krotoski 1990) and remains unchanged, and the DSL test demonstrate that the integrity of the nerve fiber is not affected.
5. Neither the PPB test nor the test of MVF shows any significant variation following the exposure to vibration. For fine tasks, such as the handling of small pegs, it can be concluded that previous exposure to vibration, even at high levels, does not reduce the performance of the workers.

References

Banister PA, Smith FV (1972) Vibration-induced white finger and manipulated dexterity. Br J Ind Med 29: 264–267

Bell-Krotoski JA (1990) Light touch-deep pressure testing using Semmes-Weinstein monofilaments. In: Harter JM, Schneider LM, Markin EJ, Callahan AD (eds) Rehabilitation of the hand: surgery and therapy. Mosby, St. Louis, pp 585–593

Bovenzi M (1990) Medical aspects of the hand-arm vibration syndrome. Int J Ind Ergonomics 6: 61–73

Bovenzi M, Petronio L, Di Marino F (1980) Epidemiological survey of shipyard workers exposed to hand-arm vibration. Int Arch Occup Environ Health 46: 251–266

Brammer AJ, Taylor W, Lundborg G (1987) Sensorineural stages of the hand-arm vibration syndrome. Scand J Work Environ Health 13: 279–283

Durnil WG, Rosecrance JC, Cook TM, Birgen WS, Dostal AJ, McMurray SJ (1993) Reliability of distal sensory latency measures of the median nerve using an electroneurometer. J Occup Rehabil 3: 105–112

Färkkila M (1978) Grip force in vibration disease. Scand J Work Environ Health 4: 159–166

Färkkila M, Pyykkö I, Korhonen O, Starck J (1980) Vibration-induced decrease in the muscle force in lumberjacks. Eur J Appl Physiol 43: 1–9

Färkkila M, Aatola S, Stark J, Krohonen O., Pyykkö I (1986) Hand-grip force in lumberjacks: two-year follow-up. Int Arch Occup Environ Health 58: 203–208

Hammarskjöld E, Harms-Ringdahl K, Ekholm J, Samuelson B (1991) Effect of short-time vibration exposure on work movements with carpenters' hand tools. Int J Ind Ergonomics 8: 125–134

Harada N, Griffin MJ (1991) Factors influencing vibration sense thresholds used to assess occupational exposure to hand transmitted vibration. Br J Ind Med 48: 185–192

ISO 5349 (1986) Mechanical vibration. Guidelines for the measurement and the assessment of human exposure to hand-transmitted vibration. International Organisation for Standardisation, Geneva

Johansson RS, Vallbo AB, Westling G (1980) Thresholds of mechanoreceptive afferents in the human hand as measured with von Frey hairs. Brain Res 184: 343–351

Lidström IM, Hagelthorn G, Bjerker N (1982) Vibration perception in persons not previously exposed to local vibration – exposed workers. In: Brammer AJ, Taylor W (eds) Vibration effects on the hand and arm in industry. Wiley, New York, pp 59–66

Lundborg G, Dahlin L, Lundström R, Necking L, Strömberg T (1992) Vibrotactile function of the hand in compression and vibration-induced neuropathy. Scand J Plast Reconstr Hand Surg 26: 275–279

Lundström RJL (1986) Responses of mechanoreceptive afferent units in the glabrous skin of the human hand to vibration. Scand J Work Environ Health 12: 413–416

Lundström R, Strömberg T, Lundborg G (1992) Vibrotactile perception threshold measurements for diagnosis of sensory neuropathy. Int Arch Occup Environ Health 64: 201–207

Maeda S, Griffin MJ (1993) Temporary threshold shifts in fingertip vibratory sensation from hand-transmitted vibration and repetitive shock. Br J Ind Med 50: 360–367

Maeda S, Griffin MJ (1994) A comparison of vibrotactile thresholds on the finger obtained with different equipment. Ergonomics 37: 1391–1406

Malchaire J, Piette A, Rodriguez Diaz LS (1998) Temporary threshold shift of the vibration perception threshold following a short duration exposure to vibration. Ann occup Hyg (in press)

Nishiyama K, Watanabe S (1981) Temporary threshold shift of vibratory sensation after clasping a vibrating handle. Int Arch Occup Environ Health 49: 21–33

Nishiyama K, Toada K, Yamashita H, Watanabe S (1994) Application of a new, self-recording, vibratory sensation meter to measure temporary threshold shift of vibratory sensation caused by local vibration exposure. Int Arch Occup Environ Health 66: 97–102

Takamatsu M, Futatsuka M, Sakurai T, Matoba T, Gotoh M, Aoyama H, et al (1982) A study of the extent and scope of local vibration hazards in Japan. Ind Health 20: 177–190

Thonnard JL, Masset D, Penta M, Piette A, Malchaire J (1997) Short term effect of hand-arm vibration exposure on tactile sensitivity and manual skill. Scand J Work Environ Health 23: 193–198

Tiffin J, Asher EJ (1948) The Purdue pegboard: norms and studies of reliability and validity. J Appl Psychol 32: 234–247