Vibration Injury Network

Research Network on Detection and Prevention of Injuries due to Occupational Vibration Exposures

Neurological and Functional Effects of Short Term Exposure to Hand-Arm Vibration

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Report on three experimental studies to quantify the frequency and amplitude dependencies of the sensory and functional effects resulting from short term (10 to 40 min) exposures to hand-arm vibration.

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ABSTRACT

Objectives:

The aim of this series of three studies was to quantify the frequency and amplitude dependencies of the sensory and functional effects resulting from short term (10 to 40 min) exposures to hand-arm vibration.

Material and methods

In study 1, 13 subjects undertook 9 experiments, grasping during 32 minutes (axis Y) a handle vibrating at 5, 20 or 80 ms^{-2} at 31.5, 125 or 500 Hz. A reference experiment was conducted without vibration.
In study 2, 12 subjects performed similar experiments lasting 10, 20 and 40 min at 40 ms^{-2}, 125 Hz.
In study 3, 12 subjects performed three experiments with "equal energy": 40 min at 28 ms^{-2}, 20 min at 40 ms^{-2}, and 10 min at 56 ms^{-2}, 125 Hz, as well as, again, the reference experiment.

Two sensory tests (vibration perception threshold (VPT) and pressure perception threshold (PPT)), two functional tests (Purdue Pegboard (PPB) and maximum voluntary force (MVF)), and a questionnaire concerning the perceived paresthesia and numbness were taken before, during and after exposure.

Results

All the tests, beside VPT and perceived paresthesia, failed to show any effect that could be related to vibration instead of muscular and postural constraints.

Study 1 demonstrated that the VPT after exposure (VPT_1) varies as a function of exposure accelerations and frequencies. Although the effects appear to be slightly different for the VPT at the test frequencies of 31.5 Hz and 125 Hz, the general relationship can be described as:

$$VPT_1 = 54.8 + 0.519\ VPT_0 + 9.377 \log A$$

with A the unweighted amplitude and VPT_0 the pre-exposure value.
As far as the frequency effect is concerned, the same VPT variation appeared to result from an exposure to A ms^{-2} at 31.5 Hz, $0.45 \times A$ ms^{-2} at 125 Hz and $1.40 \times A$ ms^{-2} at 500 Hz. This definitely invalidates the ISO 5349 weighting scheme and it is proposed to use the unweighted amplitude to better assess the risk of neurological disorders

Experiments in studies 2 and 3 with respectively strongly different and equal energy exposures led to the same order of magnitude of VPT variations, invalidating therefore the "equal energy" principle.

Conclusions

10 to 40 min vibration exposures lead to potentially strong variations of VPT and paresthesia in the short term. These effects are better predicted on the basis of the unweighted acceleration amplitude and do not obey the "equal energy" principle. The tests commonly used for dexterity or functional capacity fail to measure any effect that could be in association with the exposure to vibration.

INTRODUCTION

Several authors (Lidström et al. 1982, Lundström 1986, Lundström et al. 1992, Lundborg et al. 1992, Maeda and Griffin 1994; Malchaire et al, 1998) have shown that, following an exposure to vibration, the sensitivity of mechanoreceptors in the fingers is temporary altered and the subjects suffer from paresthesia and numbness (Takamatsu et al. 1982, Bovenzi et al. 1980).
Many questions remain however concerning the magnitude of these temporary modifications, the frequency and time dependencies as well as their possible repercussions on work safety.
The aims of the present series of researches are:

- Study 1: to investigate these magnitudes at different acceleration levels and at different frequencies and study the validity of the frequency-weighting curve proposed in ISO 5349 (1986) for neurological effects.
- Study 2: to investigate how these temporary alterations vary as a function of the duration of exposure.
- Study 3: to investigate whether the equal energy principle applies, that is, whether the same alterations are observed from exposures of different durations D and amplitudes A such that $A^2 D$ remains constant
- In the three studies, to determine whether these temporary modifications result in decreased force or impaired dexterity.

MATERIAL AND METHODS

Material

All three researches used the same technical facilities:

- Vibration generated using a Tektronix TM 503 frequency generator, connected to a B&K4808 shaker, via a Harfield 2U600 MDS-FET power amplifier.
- Vertical handle mounted on the shaker and grasped (axis Y, ISO 5349) by the subject with a force of 20N. The handle is thermo regulated at 32°C and equipped with a strain gauge to monitor the grip force.
- Shaker counterbalanced and mounted vertically near its centre of gravity so that the lifting force (2 N) and torque are about nil.
- Subjects seated with the right forearm bent at 90° and resting on a soft support adjusted in height, the hand in neutral position.

Four sensory and functional tests were performed on the right hand.

1. The vibration perception threshold test (VPT) at 31.5 and 125 Hz, using a minishaker B & K 4810, mounted on a balance and excited from a modified audiometer (Madsen Micromate 304). The force on the pulp of the test finger (second finger) (contact surface 5 mm^2) was kept constant at 0.2 N. The dynamic range of the system was from 50 to 160 dB (ref 10^{-6} ms^{-2}) (0.3 mms^{-2} to 100 ms^{-2}). The testing procedure consisted in increasing the level progressively (by steps of 5 dB) until the subject reacted and then decreasing and increasing again the level in order to cross the threshold three times.

2. The pressure perception threshold test (PPT), 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 maximum voluntary grip force (MVF) using a JAMAR PC5031J1 dynamometer. The recorded value was the maximum force held during 3 s.
4. The Purdue Pegboard test (PPB) as test of manual dexterity (Tiffin and Asher 1948, Banister and Smith 1972). The recorded value was the number of pegs placed correctly in 30 seconds.

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

Protocol

All the tests were performed three times before the exposure to vibration. They were repeated just after the end of the exposure, as well as after 5, 10, 15 and 20 min of recovery.

Male subjects (age ranging from 25 to 35 years) without any history of peripheral or central neuropathy nor of upper limb disorders and never occupationally exposed to vibration were recruited, fully informed of the objectives and the protocol and accepted freely to participate in the study

Study 1: Frequency dependency

13 subjects performed 10 experiments, at 5, 20 and 80 ms^{-2} (unweighted) at 31.5 (conditions 1 to 3), 125 (conditions 4 to 6), and 500 Hz (conditions 7 to 9), as well as a reference condition (numbered 0) without vibration. Each experiment lasted about 90 minutes. The 10 conditions were randomised, with each person performing 5 experiments in the morning and 5 in the afternoon. At least 24 h separated 2 consecutive experiments. The exposure to vibration lasted 32 minutes.

Study 2: Time dependency

12 subjects participated in three experimental conditions with exposure to unweighted acceleration of $A = 40\ ms^{-2}$ at 125 Hz during 10, 20 and 40 minutes. Again, the reference condition without vibration was planned.
A balanced incomplete block design was used so that each subject performed only 2 of the 4 experiments (table 1).

Study 3: Equal energy principle

12 subjects participated in three experimental conditions with exposure to unweighted acceleration of
28 ms^{-2} during 40 minutes, 40 ms^{-2} during 20 minutes, and 56 ms^{-2} during 10 minutes, all three giving about the same vibration energy $A^2 \times d = 31360\ m^2s^{-3}$. Again, the reference condition without vibration was included in the protocol.

The same balanced incomplete block design than in study 2 was used. As two conditions (reference and 40 ms^{-2} 20') were common to the two studies, the data from the experiments of study 2 were reused and simply completed by the experiments described in table 2.

Statistical analysis

The results of each test were analysed using a multiple analysis of variance with the subjects, the exposure conditions and the moments of measurements as factors. The significance of the differences between the 10 exposure conditions was analysed using the least square difference method.

I. RESULTS

Study 1: Amplitude and frequency dependencies

The means and the standard deviations of the vibration perception thresholds (VPT) before and after exposure in the 9 exposure conditions are given in table 3 and illustrated in figure 1.

A general linear model was used to predict the VPT after exposure (VPT_1) as a function of the threshold before (VPT_0) and the logarithm (base 10) of the unweighted amplitude, while taking account of the subject and the frequency effects.

At the test frequency of 31.5, the expression found is:

$$VPT_{1,31.5} = 79.4 + 0.344\ VPT_{0,31.5} + 6.896 \log A + K \qquad (R^2 = 0.597)$$

with K being the frequency effects equal to 0.30, 1.14 and -1.44 dB at the exposure frequencies of 31.5, 125 and 500 Hz.

With respect to the exposure frequency of 31.5 Hz, the effect is therefore +0.83 dB at 125 Hz and –1.74 dB at 500 Hz.
As VPT_1 increases as a function of 6.896 log A, this means that an exposure to an acceleration amplitude smaller by a factor of 0.76 at the exposure frequency of 125 Hz would produce the same increase in VPT than at 31.5 Hz. At the exposure frequency of 500 Hz on the contrary, the amplitude should be increased by a factor 1.79. Figure 2 shows this frequency weighting.

At the test frequency of 125 Hz, the results are:

$$VPT_{1,125} = 53.1 + 0.486\ VPT_{0,125} + 11.873 \log A + K \qquad (R^2 = 0.788)$$

where K is the frequency effect, equal to –1.47, 4.17 and –2.70 dB at the exposure frequencies of 31.5, 125, 500 Hz respectively.

With respect to the exposure frequency of 31.5 Hz, these effects are therefore 5.63 dB at 125 Hz and –.24 dB at the exposure frequency of 500 Hz, implying that, at these two exposure frequencies, the amplitude must be respectively multiplied by a factor 0.34 (reduction) and 1.27 (increase) to lead to the same variation in VPT than at the exposure frequency of 31.5 Hz.

Figure 2 shows this frequency weighting as well as the weighting proposed in ISO 5349.

It can therefore be concluded that, as far as the vibration perception threshold is concerned, and therefore the sensitivity of the mechanoreceptors and the development of temporary neurological impairment, the ISO frequency weighting has no value.

The two frequency weightings found for the two test frequencies show both an increased sensitivity at 125 Hz and a decreased sensitivity at 500 Hz compared to 31.5 Hz. As a unique frequency weighting should be proposed in correlation with neurological effects, the general linear model was used on both sets of data together, taking into account a "test frequency" effects.

The model is

$$VPT_1 = 54.8 + 0.519\ VPT_0 + 9.377 \log A + K, \qquad (R^2 = 0.825)$$

with exposure frequency effect K being equal to of –0.63, 2.66 and –2.02 dB for 31.5, 125 and 500 Hz respectively, or with respect of 31.5 Hz, 3.29 and –1.39 dB for 125 and 500 Hz.

The reduction or increase factors are then 0.45 and 1.40 respectively, or else –7 dB and +3 dB.

As far as the other test are concerned, the main conclusions of the study are:

- The symptoms of paresthesia after exposure showed large interindividual differences and a slight increase as a function of the acceleration amplitude, regardless of the frequency, according to:
  $$\text{Sensation} = 2.9 + 0.018\ A \qquad (R = 0.430)$$
- The statistical analyses demonstrated very significant differences between subjects ($p < 0.001$) for each of the other tests (beside VPT discussed below), but incidental or no variation as a function of the vibration acceleration or frequency.
- PPT increased in average by 1 or 2 monofilaments compared to the reference condition without vibration. These changes correspond to increases in force from 1.7mN to 4.1 or 7.0 mN. These very small variations do not represent a significant alteration in the perception of the pressure according to the scale proposed by Bell-Krotoski (1990).
- MVF decreased significantly and the numbness sensation increased in association with the gripping of the handle and not with the vibration exposure.
- The variations in the Purdue Pegboard scores tests were no significantly associated with the exposure to vibration.

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

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

Paresthesia and numbness are clearly the main effects recognised by the subjects and those for which they complained. While the numbness symptoms and the major part of the paresthesia are due to the grip of the tool, the paresthesia symptoms increase with the amplitude of vibration. The time constant of the phenomenon is about 8 minutes, meaning that more than 20 minutes are needed for the subjects to recover substantially. It can therefore be expected that, in many industrial settings, the workers endure repetitively this type of symptoms.

Study 2: Time dependency

Table 4 gives the means of the vibration perception thresholds before and directly after the exposures in the 4 conditions. Due to the statistical design used, only the mean values provided by the analysis of variance can be compared as they are corrected for the subject effects. Therefore the standard deviation is the same for the means in the four conditions.

The $VPT_{31.5}$ shows a slight increase with the duration of the exposure. This proves to be highly significant (0.20 x duration, $p<0.002$) when the subject effects are taken into account. It is no longer the case when these effects are averaged.

The VPT_{125} does not exhibit such an increase and the differences in mean VPT between the three experiments with vibration are likely to be due to inter and intra individual differences.

It must therefore be concluded that the VPT at both frequencies do not appear to be influenced by the duration of the exposure to vibration and that, after exposure duration of 10 minutes, a steady state level is reached. This is in accordance with our previous results that showed that the time constant of the increase in VPT was of the order of 3 minutes (Malchaire et al. 1998).

As in study 1, none of the other tests did show any significant modification beyond the effects associated with gripping the handle during 40 minutes.

Study 3: Equal energy principle

Table 5 gives the means and standard deviations of the vibration perception thresholds before and directly after the exposures in the 4 conditions (values corrected again as a function of the subject effects)

The VPT increases after exposure in the three conditions with vibration are not statistically different. A slight but non significant decrease is observed from condition (28 ms^{-2}, 40') to condition (56 ms^{-2}, 10') for the test frequency of 31.5 Hz, while the variation for the test frequency of 125 Hz do not follow any model.
It must be concluded, as in study 2 on time dependency, that the three conditions investigated give rise to VPT of the same order of magnitude.

Again, none of the other tests showed any significant modification after exposure to vibration, as compared to the reference condition without vibration. Although significant alterations in the paresthesia sensation and in the PPB scores were observed, they must be linked to the fact of gripping the handle rather than to the exposure to vibration.

II. GENERAL DISCUSSION

Study 1 showed an increase in VPT with the vibration exposure amplitude. In average for the 2 test frequencies, this increase is given by: 9.377 log A, and therefore is about 3 dB (2.8) per doubling of the amplitude. The range of unweighted acceleration amplitudes considered in study 1 was large (5, 20 and 80 ms^{-2}) and covers most of the exposure conditions encountered in practice.

This study invalidated completely the frequency weighting described in ISO 5349 and showed clearly that an exposure to a 125 Hz vibration leads to greater alterations of the VPT than exposures to 31.5 and 500 Hz vibrations.
If the multiplication of weighting network – as was proposed for whole body vibration – would be scientifically defendable, it is our opinion that it would be in practice strongly unfortunate. The conclusion must then be that short-term modifications of the VPT are better predicted using the unweighted equivalent acceleration amplitude and that this should systematically be estimated, in addition to the traditional weighted value.

However, the weighting scheme is not intended to reflect the sensitivity to short term but to long-term effects. In that respect, in a recent epidemiological study (Malchaire, 2001), we arrived at the opposite conclusion that persistent complaints were in a closer relationship with the weighted acceleration amplitudes.

Study 2 did not show any further variation of the VPT when the exposure duration was increased from 10 to 20 and 40 minutes. A previous study (Malchaire et al. 1998) showed that the VPT evolved as a first-degree system with a time constant of about 3 minutes. The three durations used in this study 2 are then equal to, in average, 3, 6 and 12 time constants and, therefore, it must be understood that the same steady state value was reached in the three experiments.

These three conditions differed actually by factors of 1, 2 and 4 in terms of the total energy received by the hand of the subjects. The fact that the VPT increases were the same invalidated therefore, in itself, the "equal energy" principle.
The temporary variation is dependent of the vibration amplitude and, at least in the duration range from 10 to 40 minutes, independent of the exposure duration.

Study 3 was actually designed in the VINET research project to test the validity of this "equal energy" principle. A parallel study was performed concerning the vascular effects.
The three exposure conditions led to the same variations of VPT.
This however does not confirm the "equal energy" principle as it is in opposition with the conclusions of study 2.

Actually, the three amplitudes used in the study (28, 40 and 56 ms^{-2}) were not very different, in order to get the same energy with exposure durations in an acceptable range (10 to 40 minutes).
According to the mathematical expression derived in study 1, this ratio of 2 in amplitude leads to a difference in VPT of 2.8 dB, which is most likely masked in the results by the inter and intra individual differences.

Although the experiments, and in particular the experiments with vibration, were felt rather exhausting by the subjects, none of the tests (beside VPT) showed any significant effect that can be associated with vibration. The main physiological constraint must be therefore considered as being the muscular constraint - postures and forces.

While the VPT modifications in some experiments in study 1 were quite large, they did not appear associated – at least in the short term – to any alteration measured by the other tests. The reasons for this lack of association need further investigation and more sensible or adequate tests must be found. In particular, the Purdue Pegboard test appears not sensible enough to reflect the observable – but not quantifiable – dexterity problems some subjects had picking the pegs. The reason for this is most likely that oculomotor coordination made it possible to adapt rather quickly the strategy used for picking and placing the pegs. More adequate tests should not make this compensation possible.

The signification and implications of these VPT modifications must also be assessed. The subjects did not notice or complain about those modifications, but primarily about the tingling and numbness sensations, obvious and undeniable but not quantifiable. These sensations were concomitant with the VPT modifications but appeared to follow another time evolution both during their development and during recovery. They also were partly due to gripping.

At the end of the study, a few points remain to be investigated:

- What determine the significant differences in response between subjects?
- How these short-term variations in VPT and sensations do they lead to permanent impairment in the long term?
- The subjects with the strongest short-term response are they more likely to develop permanent damage or, as in the case of noise, the two phenomena are they independent?

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Table 1 – Balanced incomplete block design for study 2

Experiment	Subject											
	1	2	3	4	5	6	7	8	9	10	11	12
No vibration	x	x	x	x	x	x						
40 ms^{-2} 10'			x			x		x		x	x	x
40 ms^{-2} 20'	x			x			x	x	x	x		
40 ms^{-2} 40'		x			x		x		x		x	x

Table 2 – Balanced incomplete block design for study 2 (complementary experiments)

Experiment	Subject											
	1	2	3	4	5	6	7	8	9	10	13	14
28 ms^{-2} 40'		x			x		x		x		x	x
58 ms^{-2} 10'			x			x		x		x	x	x

Table 3 – Vibration perception thresholds (VPT) before and after exposure in the 9 exposure conditions (mean values and standard deviations for the 13 subjects)

Exposure Condition	Exposure frequency (Hz)	Exposure acceleration (ms^{-2})	$VPT_{0\ 31.5}$ (dB) m (s)	$VPT_{1\ 31.5}$ (dB) m (s)	$VPT_{0\ 125}$ (dB) m (s)	$VPT_{1\ 125}$ (dB) m (s)
1	31.5	5	114.1 (2.3)	123.5 (3.8)	96.4 (2.5)	107.7 (4.4)
2	31.5	20	114.6 (1.2)	128.5 (2.4)	97.2 (3.4)	112.3 (4.8)
3	31.5	80	113.7 (2.3)	131.9 (3.3)	97.1 (3.3)	122.7 (4.4)
4	125	5	113.7 (2.3)	125.4 (3.2)	96.3 (2.7)	111.9 (3.3)
5	125	20	113.1 (2.7)	127.3 (2.6)	96.4 (3.0)	117.3 (3.9)
6	125	80	114.0 (3.4)	133.1 (3.3)	96.4 (3.5)	129.6 (3.2)
7	500	5	113.2 (2.6)	121.9 (4.3)	96.0 (3.6)	107.7 (2.6)
8	500	20	112.9 (2.4)	125.0 (3.5)	95.5 (3.4)	111.5 (3.8)
9	500	80	113.6 (2.8)	130.8 (2.8)	95.6 (3.8)	118.1 (3.8)

Table 4 - Means of the vibration perception thresholds before and directly after the exposures in the 4 conditions

Parameter		**Experiment**				
		Means				**Standard deviation**
		Reference	**40 ms^{-2} 10'**	**40 ms^{-2} 20'**	**40 ms^{-2} 40'**	
$VPT_{31.5}$	**Before**	107.1	109.2	108.8	109.2	1.3
	After	114.8	118.5	122.9	125.4	2.2
VPT_{125}	**Before**	101.1	102.1	102.6	101.1	1.5
	After	108.3	117.7	121.5	118.3	1.8

Table 5 - Means and standard deviations of the vibration perception thresholds before and directly after the exposures in the 4 conditions

Parameter		**Experiment**				
		Means				**Standard Deviation**
		Reference	**28 ms^{-2} 40'**	**40 ms^{-2} 20'**	**56 ms^{-2} 10'**	
$VPT_{31.5}$	**Before**	106.2	108.9	108.5	109.5	1.4
	After	113.7	125.6	123.7	121.9	1.1
VPT_{125}	**Before**	99.4	100.6	101.9	101.4	1.6
	After	107.9	116.7	121.7	120.4	1.9

Figure 1 - Vibration perception thresholds (VPT) after the exposure as a function of acceleration amplitude and frequency exposure

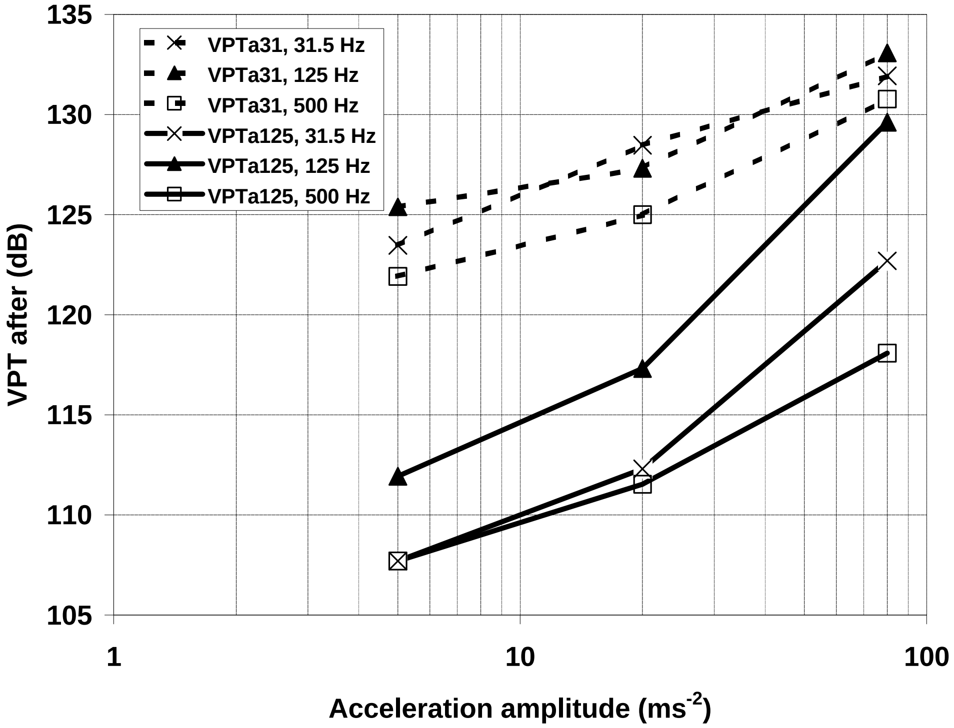

Figure 2 - Frequency weighting factors according to ISO5349 and the results of study 1