Risks of Occupational Vibration Exposures

VIBRISKS

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Annex 6 to Final Technical Report

Title: Experimental studies of acute effects of hand-transmitted vibration on vascular function

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Summary

In the VIBRISKS project, three experimental studies were designed and conducted with the aim of investigating the acute vascular effects of hand-transmitted vibration in healthy men. Study 1 explored the relation between acute vascular effects and (i) vibration magnitude, (iii) vibration frequency, (iii) exposure duration, and (iv) alternative measures of vibration dose of the general form: $dose = a^m t^n$, where a and t are the acceleration magnitude and the duration of vibration exposure, respectively. It was found that a measure of dose that better reflects the digital vasoconstriction following vibration exposure is at (or possibly at^2). The use of at during the day (as well as over years) would make the calculation of 'dose' easier. It would also put more 'weight' on the duration of daily exposures to hand-transmitted vibration than when using the a^2t relationship underlying the current calculation of the daily A(8). Study 1, moreover, investigated the acute response of finger circulation to vibration with different combinations of magnitude and duration but with the same "energy-equivalent" acceleration magnitude according to current standards for hand-transmitted vibration. For the range of vibration magnitudes investigated (44 to 176 m/s^2 r.m.s. unweighted; 5.5 to 22 m/s^2 r.m.s. when frequency-weighted according to ISO 5349), the vasoconstriction during exposure to 125-Hz vibration was independent of vibration magnitude. The after-effect of vibration was different for stimuli having the same "energy-equivalent" acceleration, with greater effects following longer durations of exposure. The "energy-equivalent" acceleration failed to predict the acute effects of vibration both during and following vibration exposure. Study 2 compared the acute response of finger circulation to continuous and intermittent vibration having the same total duration of vibration exposure and the same energy-equivalent acceleration magnitude. For the vibration stimuli investigated (exposure durations varying from 1.88 minutes to 30 minutes, with rest periods varying from 1.88 minutes to 15 minutes), the reduction of FBF during exposure was the same for continuous and intermittent vibration. The after-effect of vibration was greater following the continuous vibration exposure. Although some evidence from this study is consistent with intermittent vibration having a less severe effect than continuous vibration, this evidence is not yet conclusive. Study 3 investigated the combined effects of force and vibration on finger circulation. Push forces of three magnitudes (0, 2, and 5 N) and vibration with two frequencies (31.5

and 125 Hz) and two magnitudes (2 and 8 m/s^2 frequency weighted) were used. Modest levels of force applied by a finger had a large effect on the finger blood flow, possibly due to the constriction of local blood vessels. The acute vascular effects of vibration caused additional reductions in finger blood flow that were not limited to the finger experiencing force and vibration. In all fingers (exposed and not exposed to vibration), the greater the magnitude of vibration, the greater the reduction in finger blood flow. In all fingers (exposed and not exposed to vibration), when the vibration was frequency-weighted according to current standards, 125 Hz vibration caused greater reductions in finger blood flow than 31.5 Hz vibration.

1. Introduction

One of the tasks of Work Package (WP) 3 in the VIBRISKS project was to conduct "***Laboratory studies of vascular effects of hand-transmitted vibration***". The aim of the experimental studies of the acute effects of hand-transmitted vibration was to provide improved "weightings" for the effects of the frequency and direction of hand-tool vibration, and grip force exerted by operators. These are required for the interpretation of the epidemiological data and the establishment of appropriate dose response models in Work Package 1 (HTV epidemiological studies).

Three experimental studies have been designed and conducted by the Clinical Unit of Occupational Medicine, University of Trieste (Italy) and the Human Factors Research Unit, ISVR, University of Southampton (UK):

Study 1 consists of reanalysis of the findings of previous investigations on the vascular effects of 125-Hz vibration with different magnitudes (from 1 to 176 ms^{-2} rms) and durations (from 0.03 to 1 hour). The various exposure conditions have been combined to obtain alternative measures of vibration dose with different time dependency:

$$dose = a^m t^n$$

where a and t are the acceleration magnitude and the duration of vibration exposure, respectively. Doses with different combinations of m = 0, 1, and 2, and n = 0, 1, and 2 (i.e. a^0t, at^0, at, a^2t, and at^2) were computed for each subject who participated in the experimental investigations described in the previous sections.

The relation between acute vascular effects and (i) vibration magnitude, (iii) vibration frequency, (iii) exposure duration, and (iv) alternative measures of vibration dose has been assessed. A further aims was to investigate the acute response of finger circulation to vibration with different combinations of magnitude and duration but with the same "energy-equivalent" acceleration magnitude according to current standards for hand-transmitted vibration.

Study 2 compares the acute response of finger circulation to continuous and intermittent vibration having the same total duration of vibration exposure and the same energy-equivalent acceleration magnitude.

The effect of intermittency has been tested using a 125-Hz vibration with a constant acceleration magnitude (44 ms^{-2} rms) and a constant total exposure duration (30 minutes). Periods of regular vibration exposure were broken with rest periods of the same duration.

Study 3 investigates the combined effects of force and vibration on finger circulation. Push forces of three magnitudes will be used (0, 2, and 5 N). Vibration with two frequencies (31.5 and 125 Hz) and two magnitudes (2 and 8 ms^{-2} frequency weighted) have been used.

This Annex No.6 to the Final Report illustrates in detail the findings of the above-mentioned experimental studies.

Section 2

STUDY 1

ACUTE EFFECTS OF MAGNITUDE, FREQUENCY, AND DURATION OF HAND-TRANSMITTED VIBRATION ON FINGER BLOOD FLOW

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2.1 Introduction

The aims of the experimental studies presented in this section of VIBRISKS Deliverable 14a were to investigate the effect of magnitude, frequency, and duration of vibration on finger blood flow in normal men.

Using vibration magnitude and exposure duration data from our published and unpublished experimental studies [2-8], the relations between various measures of vibration dose with different time dependencies and the acute vascular effects in the fingers of the exposed subjects were studied. A further aim was to investigate the acute response of finger circulation to vibration with different combinations of magnitude and duration but with the same "energy-equivalent" acceleration magnitude according to current standards for hand-transmitted vibration.

2.2 Subjects and Methods

2.2.1 Subjects

Each experiment involved ten healthy men (age range: 21 to 46 years). All subjects were students or office workers with no history of regular use of hand-held vibrating tools in occupational or leisure activities. Most of the subjects (90%) were non-smokers. None of them reported cardiovascular or neurological disorders, connective tissue diseases, injuries to the upper extremities or a family history of Raynaud's phenomenon. They completed in a health questionnaire, read a list of medical contraindications and gave written informed consent to the studies. All investigations were approved by the Human Experimental Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton (UK).

2.2.2 Measurement of finger blood flow

The measures of finger blood flow (FBF) were obtained by a strain-gauge plethysmographic technique. Methods for measuring FBF have been reported in more detail in the original papers [2-8]. Briefly, mercury-in-Silastic strain gauges were placed at the base of the finger nails and PVC plastic cuffs (2.4 × 9 cm) were

fixed around the proximal phalanges and secured by a Velcro strip. The measures of FBF were obtained by a venous occlusion technique. After calibrating the strain gauge, the pneumatic cuffs were instantaneously inflated to a pressure of between 40 and 60 mmHg and the rise of fingertip volume was detected by the strain gauge. The FBF was obtained from the plethysmographic tracings according to the criteria of Greenfield *et al.* [11]. The FBF measurements were expressed in absolute values (ml/100 ml/min, or ml/100 ml/s) and as a percentage of the pre-exposure values (%).

2.2.3 Experimental procedures

The experiments were conducted in a laboratory with mean (SD) air temperature of 25.7 (0.6)ºC. The subjects wore light clothing and lay supine on an examination couch, the hands being positioned over the chest, just above the level of the heart. After obtaining baseline FBF measurements, and while remaining supine, the subjects were asked to place their right (exposed) hand palm downward on a wooden surface (100 mm × 100 mm) secured to the table of an electrodynamic vibrator. in all experiments, all five fingers of the exposed hand were in contact with the wooden surface, while the left (non-exposed) hand was positioned palm downward on a wooden table at a similar height and just above the level of the heart. Visual feedback through an analogue meter allowed subjects to maintain a constant downward force of 10 N with the right hand. Sinusoidal vibration in the vertical direction was produced by an electrodynamic vibrator. Different combinations of frequency, magnitude and duration of vibration were presented according to the experimental protocols. FBF was measured in the fingers (usually the middle finger) of both the exposed and unexposed hand. The arrangement for generation of vibration, control of contact force, and measurement of FBF has been described in more detail in the original papers [2-8].

2.2.4 Data analysis

Data analysis was performed using the software package Stata (Stata Corporation, versions 5.0 to 9.2 SE). The data were summarised with the mean as a measure of central tendency and the standard deviation (SD) or standard error of mean (SEM) as measures of dispersion. The difference between paired means was tested by the Student *t*-test.

Repeated measures analysis of variance (ANOVA) was used to test the hypothesis of no difference in the vascular responses in different exposure conditions. When the compound symmetry assumption (that is, the measures have the same variance and the correlations between each pair of repeated measures are equal) was violated, a conservative test of the repeated measures factor was used by reducing the degrees of freedom of the *F* ratio (Greenhouse-Geisser method) [12]. The 95% Bonferroni confidence intervals for pairwise mean comparisons of the response were used when the probability value for the *F* test of repeated measures ANOVA was $p<0.05$ (two-sided).

2.3 Experimental studies

2.3.1 EFFECTS OF VIBRATION MAGNITUDE

The aim of this study was to investigate the changes in finger circulation during and after acute exposure to four different magnitudes of hand-transmitted vibration [4].

2.3.1.1 Methods

With a static load of 10 N, the right hand of the subject was exposed to sinusoidal vibration in the vertical direction at a frequency of 125 Hz and a root-mean-square (r.m.s.) acceleration of either 5.5, 22, 44, or 62 m/s^2 (unweighted). The exposure duration on each occasion was 15 minutes. The measurements of FBF were made in both the exposed (right) and non-exposed (left) middle fingers before vibration exposure, throughout the vibration exposure period, and for 45 minutes following exposure. The measures of finger circulation were commenced at 0.5, 1.5, 3.5, 5.5, 7.5, and 15 minutes following the start of vibration. Measures were taken at the same intervals following the cessation of vibration and then at each 7.5-minute interval during the remainder of the recovery period. Each subject attended on four occasions and his right hand was exposed to a different vibration magnitude on a different day. The order of presentation of vibration magnitude was randomized. Each experimental session lasted about 1.5 hours.

2.3.1.2 Results

Vibration of any magnitude provoked significant reductions in the FBF of the vibrated finger when compared with pre-exposure FBF and contralateral (non-vibrated finger) FBF (Figure 1). Vasoconstrictor after-effects (i.e. during recovery) were observed in both fingers after the end of exposure to vibration magnitudes greater than 22 m/s^2 rms. The higher the vibration magnitude, the stronger the reduction of FBF in either finger during both vibration exposure and the recovery period. This effect was stronger in the vibrated finger than in the non-vibrated finger during both periods.

2.3.1.3 Concluding remarks

Acute exposure to 125-Hz vibration can reduce FBF in both the vibrated and the non-vibrated finger and the degree of digital vasoconstriction is related to the

magnitude of the vibration. The pattern of the haemodynamic changes during and after vibration exposure suggests that complex vasomotor mechanisms, mediated both centrally and locally, are involved in the response of digital vessel to acute vibration.

2.3.2 EFFECTS OF VIBRATION FREQUENCY

The aim of this study was to investigate the acute effects of the frequency of hand-transmitted vibration on finger circulation [5]. A further aim of this study was to investigate whether the frequency weighting assumed in current standards for hand-transmitted vibration reflects the haemodynamic changes which occur in the fingers exposed to vibration with different frequencies but with the same frequency-weighted acceleration magnitude.

2.3.2.1 Methods

With a static load of 10 N, the right hand was exposed for 15 minutes to the following unweighted r.m.s. acceleration magnitudes and frequencies of vertical vibration: 5.5 m/s^2 at 16 Hz, 11 m/s^2 at 31.5 Hz, 22 m/s^2 at 63 Hz, 44 m/s^2 at 125 Hz, and 88 m/s^2 at 250 Hz. The frequencies and unweighted r.m.s. acceleration magnitudes of vibration were chosen so as to produce the same frequency-weighted acceleration magnitude (5.5 m/s^2 r.m.s.) according to the frequency weighting recommended by ISO 5349-1 [17]. A control condition consisted of exposure to the static load only. The duration of vibration exposure was 15 minutes. The measurements of FBF were made in both the exposed (right) and non-exposed (left) middle fingers immediately before vibration exposure, throughout the vibration exposure period, and for 45 minutes following exposure. The measures of finger circulation were obtained at 0.5, 1.5, 3.5, 5.5, 7.5, and 15 minutes following the start of vibration. Measures were taken at the same intervals following the cessation of vibration and then at each 7.5 minute interval during the remainder of the recovery period. The exposure conditions were presented randomly in six separate experimental sessions with one to four days between the exposures. Each experimental session lasted about 1.5 hours.

2.3.2.2 Results

In the vibrated right finger, exposures to vibration with frequencies from 31.5 to 250 Hz provoked a greater reduction in FBF than did vibration of 16 Hz or the static load only (Figure 2). In the non-vibrated left finger, the FBF measured with vibration at each frequency from 63 to 250 Hz was significantly lower than that measured with static load only. The reduction in FBF during exposure to vibration with any frequency was stronger in the vibrated finger than in the non-vibrated finger. In both

fingers, there was a progressive decrease in FBF after the end of exposure to vibration with frequencies from 31.5 to 250 Hz. The higher the frequency of vibration, the stronger the decrease in FBF in both fingers during recovery.

2.3.2.3 Concluding remarks

Acute exposures to vibration with equal frequency-weighted magnitude reduce the FBF in both vibrated and non-vibrated fingers for frequencies between 31.5 and 250 Hz. The frequency weighting given in current standards tends to overestimate the vasoconstriction associated with acute exposures to vibration at frequencies around 16 Hz.

2.3.3 EFFECTS OF DURATION OF EXPOSURE TO VIBRATION

The aim of this study was to investigate the changes in finger circulation caused by varying the duration of exposure to hand-transmitted vibration [3].

2.3.3.1 Methods

With a static load of 10 N, the right hand of the subject was exposed for 7.5, 15, and 30 minutes to a vibration with a frequency of 125 Hz and an r.m.s. acceleration of 87 ms^{-2}. The FBF was measured before, during and after vibration exposure in both the vibrated (right) and the non-vibrated (left) middle fingers. The measures of finger circulation were taken at regular time intervals: at 0.5, 3.25 and 7.5 minutes and then at every 7.5 minutes during exposure to vibration. Measures were taken at similar intervals during a recovery period of 45 minutes. The exposure conditions were presented randomly in three separate experimental sessions with 1 to 3 days between exposures. Each measurement session lasted between 1.5 and 2 hours.

2.3.3.2 Results

During exposure to each vibration duration, the vibrated finger showed reductions of FBF which were significant when compared to the measurements taken in the same finger before exposure and when compared to the measurements in the contralateral (non-vibrated) finger during vibration exposure (Figure 3). A temporary vasodilation was observed in the vibrated finger immediately after the end of each vibration exposure. There was complete recovery to the resting values of FBF and vascular resistance after exposure to 7.5-min vibration. In contrast, a progressive reduction of FBF in both the vibrated and the non-vibrated fingers was observed during the second half of the recovery periods following exposure to both 15-min and 30-min vibration. It was observed that the longer the duration of vibration exposure the stronger the vasoconstriction in the vibrated finger during the recovery period.

2.3.3.3 Concluding remarks

Acute exposures to a vibration of 125 Hz of any duration provoked a reduction of FBF in the vibrated finger which was significant when compared with the pre-exposure measures. Vibration-induced vasoconstrictor after-effects were found to

increase as the duration of acute exposure to vibration increased. The findings of this study suggest that, in addition to the frequency and magnitude of the vibration stimulus, the duration of vibration exposure plays a role in the reaction of the digital vessels to acute vibration.

2.3.4 Measures of vibration dose

Annex C to International Standard 5349-1 suggests a tentative relationship between the occurrence of finger blanching (i.e. the onset of VWF) and vibration exposure [17]. In the ISO dose-response relationship, the prevalence of VWF is associated with three measures of occupational exposure to hand-transmitted vibration: vibration magnitude, daily exposure duration, and years of exposure. The vibration acceleration is frequency-weighted, on the assumption that the effects of different vibration frequencies varied according to an experimental study of the sensations produced by hand-transmitted vibration [18]. In the ISO standard and the European Directive 2002/44/EC on mechanical vibration [21], daily vibration exposure is expressed as 8-hour "energy-equivalent" frequency-weighted r.m.s. acceleration, $A(8)$, a measure of vibration exposure which assumes an inverse relation between daily exposure duration and the square of the frequency-weighted acceleration magnitude of the vibration. This means that if the vibration magnitude is doubled, then a four-fold reduction of the daily exposure duration is necessary to produce the same effect. This "second power" time-dependency is convenient for instrumentation and measurement procedures and is commonly assumed in r.m.s. averaging methods. Nevertheless, there is a shortage of both epidemiological and experimental data to establish that such an "energy-equivalent" time-dependency reflects the response of the hand-arm system to vibration exposures of different daily durations [1, 9, 13, 14].

In the aforementioned informative annex to ISO 5349-1, it is suggested an almost linear relationship between daily 'energy-equivalent' acceleration and the number of years of exposure for equal probability of developing VWF (e.g. $A(8)$/years = constant). The dose-response model included in the standard has allowed the severity of occupational exposures to hand-transmitted vibration to be assessed. Some subsequent epidemiological studies have reported results consistent with the predictions in the standard [1, 13, 14, 15]; others studies have reported wide differences [1, 13, 14, 15]. Risk overestimation has been mainly found in worker groups using tools with a predominantly low frequency percussive action such as road breakers, rock drills, and stone hammers. Since the ISO frequency-weighting increases the importance of low-frequency vibration, it might be argued that the

evaluation of such vibration according to the current standard does not reflect adequately the risk of vascular disorders. Conversely, some other epidemiologic surveys have pointed out that the ISO weighting may underestimate the vascular effects of vibration containing high frequency components. This seems to be consistent with the results of laboratory investigations which indicate that high-frequency vibration can induced a more powerful digital vasoconstriction than low-frequency vibration [5].

The establishment of a relationship between exposure to hand-transmitted vibration, and injury requires an appropriate means for assessing vibration dose that accounts for the observed effects of vibration magnitude, frequency, and duration, as well as factors such as push and grip forces. The findings of experimental studies of the acute effects of hand-transmitted vibration may provide improved 'weightings' for the relative importance of the various characteristics of vibration exposure. These findings are required for the interpretation of the epidemiological data and the establishment of appropriate dose-response models.

The aim of our investigations was to assess the relation between various vibration doses with different time dependency and the acute vascular effects in the fingers of the exposed subjects. A further aim was to investigate the acute response of finger circulation to vibration with different combinations of magnitude and duration but with the same "energy-equivalent" acceleration magnitude according to current standards for hand-transmitted vibration.

2.3.4.1 DOSE-RESPONSE PATTERNS FOR FINGER CIRCULATION

2.3.4.1.1 Methods

Using vibration magnitude and exposure duration data of our published and unpublished experimental studies [2-8], it was possible to construct, for each subject, various alternative vibration 'doses', of the general form:

$$dose = a^m t^n$$

where *a* and *t* are the acceleration magnitude and the duration of vibration exposure, respectively. In these doses, the relative importance of the acceleration, *a*, and the exposure duration, *t*, depends on the value of *m* and *n*. If *m* has the value 2 and *n* the value 1, the relationship between *a* and *t* is that assumed in root-mean-square averaging (as suggested in current standards to evaluate vibration exposure over a working day) [17]. Assigning values of 1 to *m* and 2 to *t* increases the "importance" of exposure duration, *t*, relative to that of vibration magnitude, *a*. Assigning a value of 1 to both *m* and *n* gives equal weight to vibration magnitude and exposure duration. With *m* = 0 the dose takes no account of vibration magnitude, while with *n* = 0 the dose takes no account of exposure duration. Doses with different combinations of *m* = 0, 1, and 2, and *n* = 0, 1, and 2 (i.e. a^0t, at^0, at, a^2t, and at^2) were computed for each subject who participated in the experimental investigations described in the previous sections.

Exposures to 125-Hz vibration with acceleration magnitudes from 1 to 176 ms^{-2} r.m.s. and durations from 0.03 to 1 hour were used to calculate doses with different time dependencies.

FBF was measured in the fingers (usually the middle finger) of both the right (exposed) hand and the left (unexposed) hand. The changes in FBF during both vibration exposure and a recovery period of 45 minutes were expressed as a percentage of the pre-exposure values (%FBF). Two outcomes for %FBF were chosen:

(i) the last measure of FBF taken at the end of both the vibration exposure and the recovery period ($\%FBF_{final}$);

(ii) the maximum reduction of FBF during both the vibration exposure and the recovery period ($\%FBF_{max}$).

The arrangement for the generation of vibration, control of contact force, and measurement of FBF has been described in more detail in the original papers [2-8].

The relation between the changes in FBF (dependent variable) and the alternative vibration doses (independent variables) was assessed by the generalised estimating

equations (GEE) approach to repeated measures data sets in order to account for the within-subject correlation [10].

The technique of fractional polynomials was used to check for the linearity of the relationship [20]. When the relationship was non-linear, the appropriate fractional polynomial transformation was applied to the predictor variable to obtain the best-fitting model.

The Bayesan Information Criterion was used as a measure of overall fit and a means to compare regression models including different measures of vibration dose [19].

2.3.4.1.2 Results

Figures 4 to 8 display the relations between $\%FBF_{final}$ and the alternative vibration doses, and Figures 9 to 13 display the relations between $\%FBF_{max}$ and vibration doses, for both the exposed and unexposed fingers during either vibration exposure or the recovery period.

2.3.4.1.2.1 EXPOSED FINGER DURING VIBRATION

During a 15-min vibration exposure, there was no overall effect of increasing vibration magnitude (i.e. dose=at^0) in the exposed finger when the changes in FBF were expressed as either $\%FBF_{final}$ (Figure 4) or $\%FBF_{max}$ (Figure 9). There was a significant reduction in both $\%FBF_{final}$ and $\%FBF_{max}$ compared with pre-exposure FBF, but no significant trend in the decrease of FBF with the increase of vibration magnitude.

During exposure to 125-Hz vibration with an acceleration magnitude of 87 ms^{-2} r.m.s. (i.e. dose=a^0t), there was a significant rise in $\%FBF_{final}$ with increasing duration of exposure (Figure 5). This finding may be explained looking at Figure 3 which shows an increase in the FBF of the exposed finger after 15 minutes of vibration exposure, suggesting a vasodilation mechanism which counteracts digital ischemia caused by prolonged exposure to hand-transmitted vibration. However, when the changes in FBF during vibration exposure was expressed as $\%FBF_{max}$, there was a marginally

non-significant reduction in FBF with increasing duration, but this finding may be explained by random variations in FBF (Figure 10).

Because of this pattern of relations between measures of %FBF and vibration magnitude or exposure duration, no dose measure (at, a^2t, or at^2) seems to be applicable for the change of %FBF in the exposed finger during vibration exposure. Figures 6 to 8 show a positive trend for $\%FBF_{final}$ with increases in vibration dose due to the vasodilation observed during prolonged exposure duration (see above). In contrast, there was a negative trend for $\%FBF_{max}$ with increasing vibration dose for at and at^2, but no clear dose-effect relationships seem to emerge from the data analysis for the exposed finger during vibration.

2.3.4.1.2.2 UNEXPOSED FINGER DURING VIBRATION

During a 15-min vibration exposure, there was an overall effect of vibration magnitude (i.e. dose=at^0) in the unexposed finger which was highly significant with $\%FBF_{max}$ (Figure 9), but marginally non-significant with $\%FBF_{final}$ (Figure 4). The effect appears to be caused by a threshold effect such that there is less reduction in %FBF at 1 ms^{-2} r.m.s. than at 2.5 ms^{-2} r.m.s. (unweighted).

During exposure to 125-Hz vibration with an acceleration magnitude of 87 ms^{-2} r.m.s. (i.e. dose=a^0t), there was no significant effect of duration on %FBF with either measure of %FBF. The trend was positive for $\%FBF_{final}$ (Figure 5) but negative for $\%FBF_{max}$ (Figure 10).

Because of this pattern of relations between measures of %FBF and vibration magnitude or exposure duration, no dose measure (at, a^2t, or at^2) seems to be applicable for the change of %FBF in the unexposed finger during vibration exposure. Figures 6 to 8 show no significant relation between $\%FBF_{final}$ and the various measures of vibration dose. As for the exposed finger during vibration, there was a negative trend for $\%FBF_{max}$ with increase in vibration doses at and at^2, but no clear pattern of dose-effect relationship seems to emerge from the data analysis for the unexposed finger during vibration.

2.3.4.1.2.3 EXPOSED FINGER DURING RECOVERY

Using both measures of %FBF, there was a significant reduction in both $\%FBF_{final}$ (Figure 4) and $\%FBF_{max}$ (Figure 9) with increasing vibration magnitude (i.e. dose=at^0) in the exposed finger during recovery.

Similarly, using both measures of %FBF, there was a significant reduction in both $\%FBF_{final}$ (Figure 5) and $\%FBF_{max}$ (Figure 10) with increasing vibration duration (i.e. dose=a^0t).

During the recovery period, significantly inverse relations between %FBF and the various measures of vibration doses (at, a^2t, or at^2) were observed in the exposed finger (Figures 6 to 8 for $\%FBF_{final}$; Figures 11 to 13 for $\%FBF_{max}$), with the exception for $\%FBF_{max}$ *vs* a^2t which was marginally not significant. Using the guidelines suggested by Raftery to compare the fit of non-nested regression models by means of the difference (Δ) in the Bayesan Information Criterion (BIC) [19], there was very strong evidence (Δ BIC > 10) that vibration doses at and at^2 performed substantially better than dose a^2t for the prediction of the response of FBF during the recovery period after the end of vibration exposure. Moreover dose at^2 was a better predictor of the effect than at (Δ BIC > 10).

2.3.4.1.2.4 UNEXPOSED FINGER DURING RECOVERY

Using both measures of %FBF, there was a significant reduction in both $\%FBF_{final}$ (Figure 4) and $\%FBF_{max}$ (Figure 9) with increasing vibration magnitude (i.e. dose=at^0) in the unexposed finger during recovery.

Similarly, using both measures of %FBF, there was a significant reduction in both $\%FBF_{final}$ (Figure 5) and $\%FBF_{max}$ (Figure 10) with increasing vibration duration (i.e. dose=a^0t).

These findings suggest that FBF in the exposed and unexposed finger during recovery after exposure are similarly affected by variations in vibration magnitude (with constant duration) and variations in duration (with constant vibration magnitude).

During the recovery period, significantly inverse relations between %FBF and the various measures of vibration doses (at, a^2t, or at^2) were observed in the unexposed finger (Figures 6 to 8 for $\%FBF_{final}$; Figures 11 to 13 for $\%FBF_{max}$), even though the relations between the two measures of %FBF and a^2t were less strong than those for at and at^2. These findings were confirmed by the BIC statistic which suggested that vibration doses at and at^2 were more powerful predictors of the response of FBF during the recovery period than dose a^2t (Δ BIC > 10). As for the exposed finger during recovery, dose at^2 was a better predictor of the vasoconstriction than at (Δ BIC > 10).

2.3.4.1.3 Concluding remarks

During exposure to vibration, the vasoconstriction in exposed and non-exposed fingers does not increase monotonically with increases in the magnitude or duration of the exposure. Consequently, it may not be possible to define a measure of dose formed from a combination of vibration magnitude and exposure duration to predict the vasoconstriction during exposure. Vasoconstriction appears immediately after the onset of vibration and, if there is any subsequent variation in FBF during prolonged exposures, it may indicate reduced vasoconstriction with increased duration of exposure. Since vibration causes reductions in FBF the effects must, to some extent, depend on the vibration magnitude. Although over all conditions previously investigated there is no significant effect of vibration magnitude, the results of an experiment to investigate the effects of variations in magnitude from 5.5 to 62 ms^{-2} r.m.s. (unweighted) found that there was increased vasoconstriction with increased magnitude of 125-Hz vibration. This suggests that if a dose measure is formed to predict the FBF during exposure it would reflect the magnitude of vibration but not the duration of exposure.

During recovery following exposure to vibration, FBF depends on both the duration and the magnitude of the prior exposure (as well as the frequency of vibration). Although there is increased vasoconstriction with both increased magnitude and increased duration, the a^2t relation used in current standards to accumulate exposures during the day is not an optimum predictor of changes in FBF. A measure of dose that better reflects the vasoconstriction following vibration exposure is at (or possibly at^2). A dose formed from at has the relation between magnitude and

duration employed to predict the incidence of finger blanching in current standards when the duration of exposure is expressed in years rather than hours in the day. The use of *at* during the day (as well as over years) would make the calculation of 'dose' easier. It would also put more 'weight' on the duration of daily exposures to hand-transmitted vibration than when using the a^2t relationship underlying the current calculation of the daily $A(8)$.

2.3.5 Effects of "energy-equivalent" combinations of vibration magnitude and exposure duration

The aim of this study was to investigate the acute response of finger circulation to vibration with different combinations of magnitude and duration but with the same "energy- equivalent" acceleration magnitude according to current standards for hand-transmitted vibration [6].

2.3.5.1 Methods

With a static load of 10 N, the right hand was exposed to 125 Hz vibration with the following unweighted r.m.s. acceleration magnitudes and durations of exposure: 44 m/s^2 for 30 minutes; 62 m/s^2 for 15 minutes; 88 m/s^2 for 7.5 minutes; 125 m/s^2 for 3.75 minutes; and 176 m/s^2 for 1.88 minutes. These vibration exposures produce the same eight-hour "energy-equivalent" frequency-weighted acceleration magnitude (~1.4 m/s^2 r.m.s.) according to International Standard ISO 5349-1 [17]. The measurements of FBF were made in both the exposed (right) and unexposed (left) middle fingers immediately before vibration exposure, throughout the vibration exposure period, and for 45 minutes following exposure. For the 30 minute period of vibration, measures of finger circulation were obtained at 0.5, 1.5, 3.5, 5.5, 7.5, 15, 22.5 and 30 minutes following the start of vibration. The first six of these measures were taken during the 15 minute exposure, the first four during the 7.5 minute exposure, the first three during the 3.75 minute exposure, and the first two during the 1.88 minute exposure. Measurements were taken at the same intervals following the cessation of vibration and then at each 7.5 minute interval during the remainder of the recovery period. The exposure conditions were presented randomly in five separate experimental sessions, lasting from about 1 to 1.5 hours, each held on a separate day.

2.3.5.2 Results

Vibration with any combination of acceleration magnitude and duration produced significant percentage reductions in the FBF of the vibrated finger when compared with the pre-exposure FBF (Figure 14). The reduction in FBF during vibration exposure was stronger in the vibrated finger than in the non-vibrated finger. Across the five experimental conditions, the various vibration stimuli caused a similar degree

of vasoconstriction in the vibrated finger during exposure to vibration. There was a progressive decrease in the FBF of both fingers after the end of exposure to vibration with acceleration magnitudes of 44 m/s^2 for 30 minutes and 62 m/s^2 for 15 minutes. No significant vasoconstrictor after-effects were found in either finger after exposure to any of the other vibration stimuli with greater acceleration magnitudes for shorter durations.

2.3.5.3 Concluding remarks

For the range of vibration magnitudes investigated (44 to 176 m/s^2 r.m.s. unweighted; 5.5 to 22 m/s^2 r.m.s. when frequency-weighted according to ISO 5349), the vasoconstriction during exposure to 125-Hz vibration was independent of vibration magnitude. The after-effect of vibration was different for stimuli having the same “energy-equivalent” acceleration, with greater effects following longer durations of exposure. The “energy-equivalent” acceleration therefore failed to predict the acute effects of vibration both during and following vibration exposure. Both central and local vasoregulatory mechanisms are likely to be involved in the response of finger circulation to acute exposures to 125 Hz vibration.

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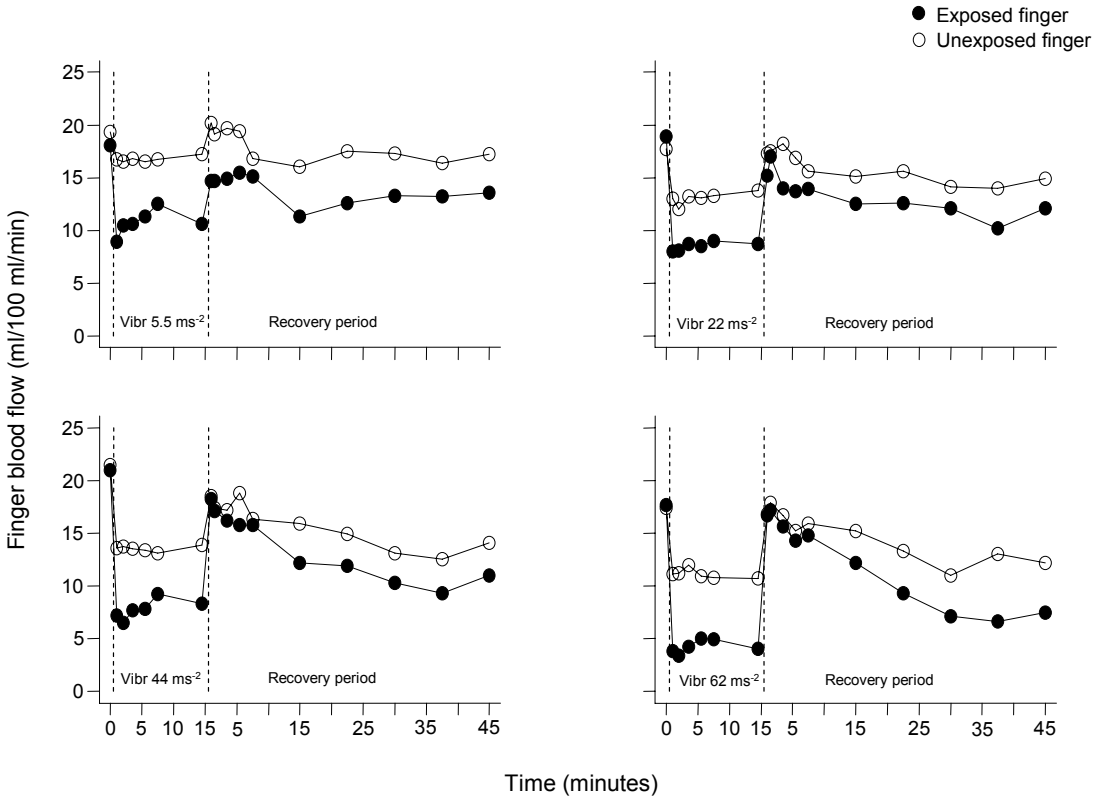

Figure 1. Mean values of finger blood flow (ml/100 ml/min) measured in ten healthy men before, during and after 15-min exposure to vibration with a frequency of 125 Hz and acceleration magnitudes of 5.5, 22, 44, and 62 ms^{-2} r.m.s. unweighted.

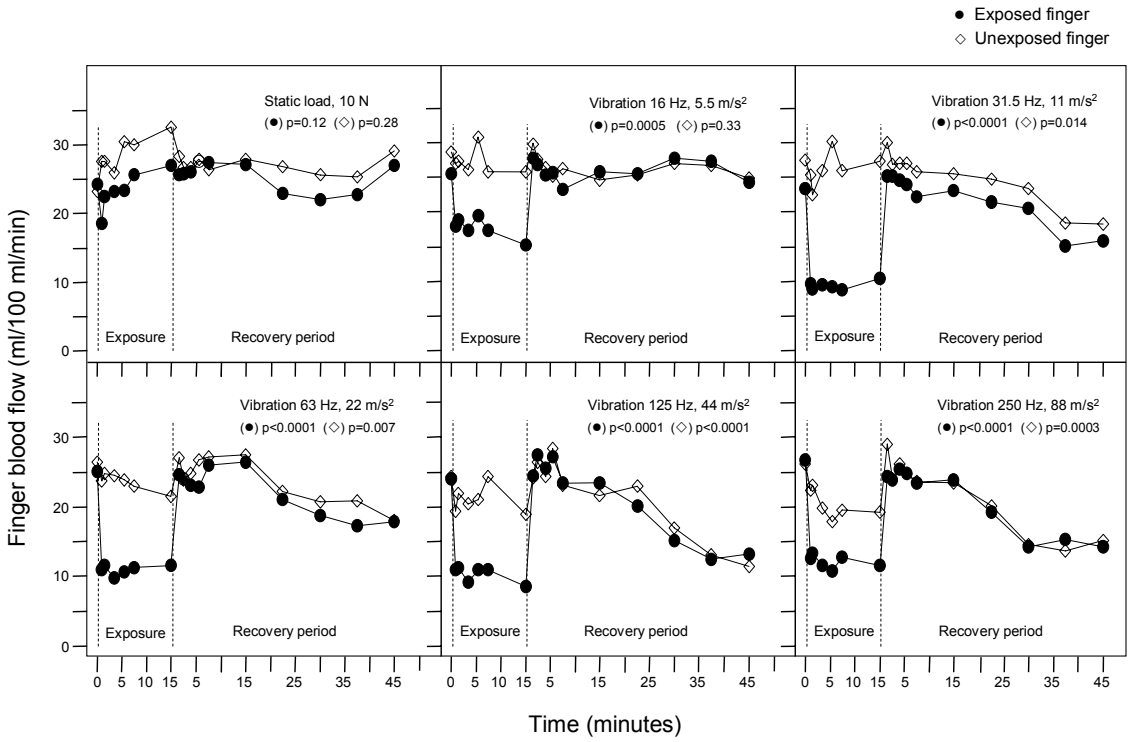

Figure 2. Mean values of finger blood flow (ml/100 ml/min) measured in ten healthy men before, during and after 15-minute exposure to static load (contact force 10 N) or vibration with different combinations of frequencies (Hz) and unweighted acceleration magnitudes (ms^{-2} r.m.s.) but with the same frequency-weighted acceleration (5.5 ms^{-2} r.m.s.) according to the frequency weighting recommended by the international standard ISO 5349.

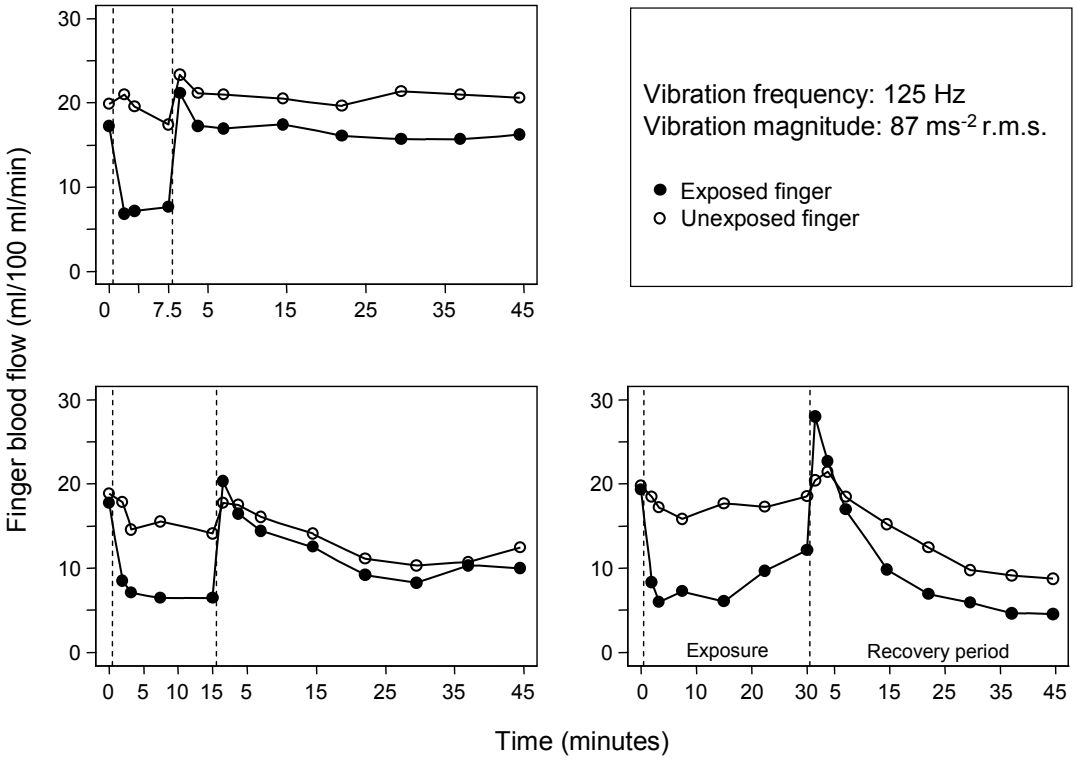

Figure 3. Mean values of finger blood blow (ml/100 ml/min) measured in ten healthy men before, during and after exposure to vibration (125 Hz, 87 ms^{-2} r.m.s. unweighted) of different duration.

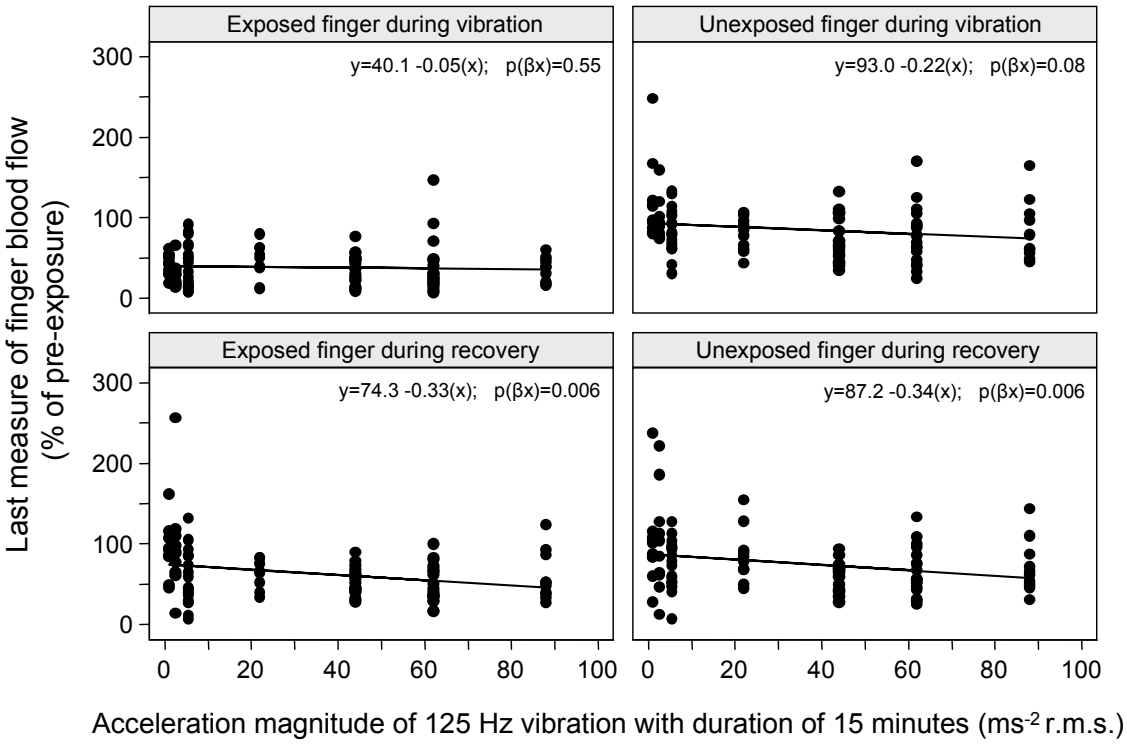

Figure 4. Percentage change of finger blood flow (FBF in % of pre-exposure) in the middle right finger (exposed finger) and the middle left finger (unexposed finger) during and after exposure to 125-Hz vibration with a duration of 15 minutes and different acceleration magnitudes (1 to 87 ms^{-2} r.m.s. unweighted). Plotted symbols are mean values of the percentage change of the last measure of FBF (% of pre-exposure) during vibration exposure and a recovery period of 45 minutes.

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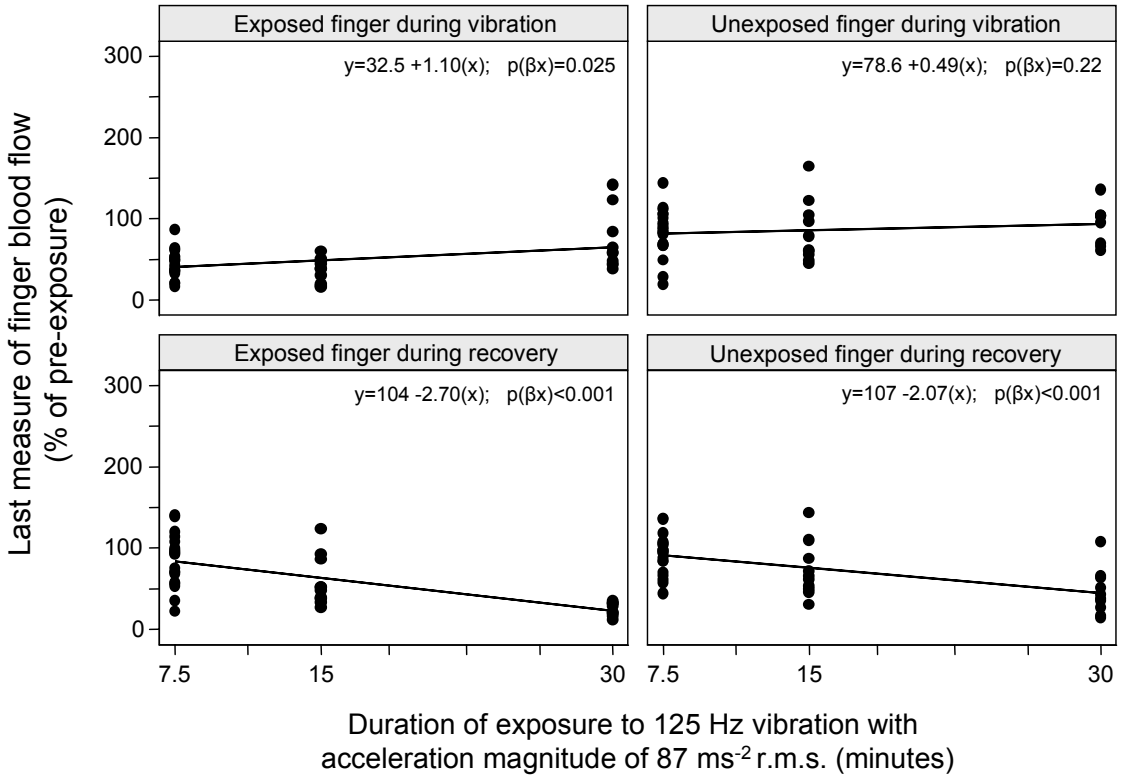

Figure 5. Percentage change of finger blood flow (FBF in % of pre-exposure) in the middle right finger (exposed finger) and the middle left finger (unexposed finger) during and after exposure to 125-Hz vibration with an acceleration magnitude of 87 ms^{-2} r.m.s. (unweighted) and different exposure durations (7.5 to 30 minutes). Plotted symbols are mean values of the last measure of FBF (% of pre-exposure) during vibration exposure and a recovery period of 45 minutes.

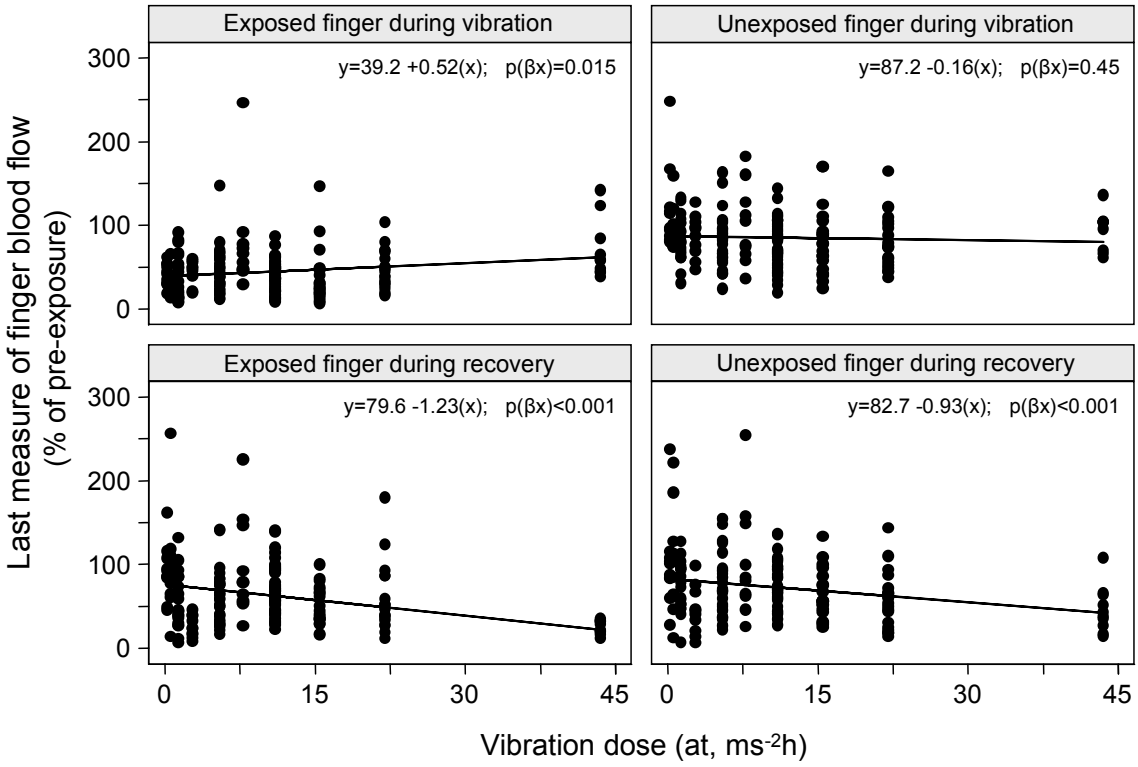

Figure 6. Percentage change of finger blood flow (FBF in % of pre-exposure) in the middle right finger (exposed finger) and the middle left finger (unexposed finger) during and after exposure to different magnitudes of vibration dose derived by combining acceleration magnitude (*a*) and exposure time (*t*), (i.e. dose=*at* in $ms^{-2}h$). Plotted symbols are mean values of the last measure of FBF (% of pre-exposure) during vibration exposure and a recovery period of 45 minutes.

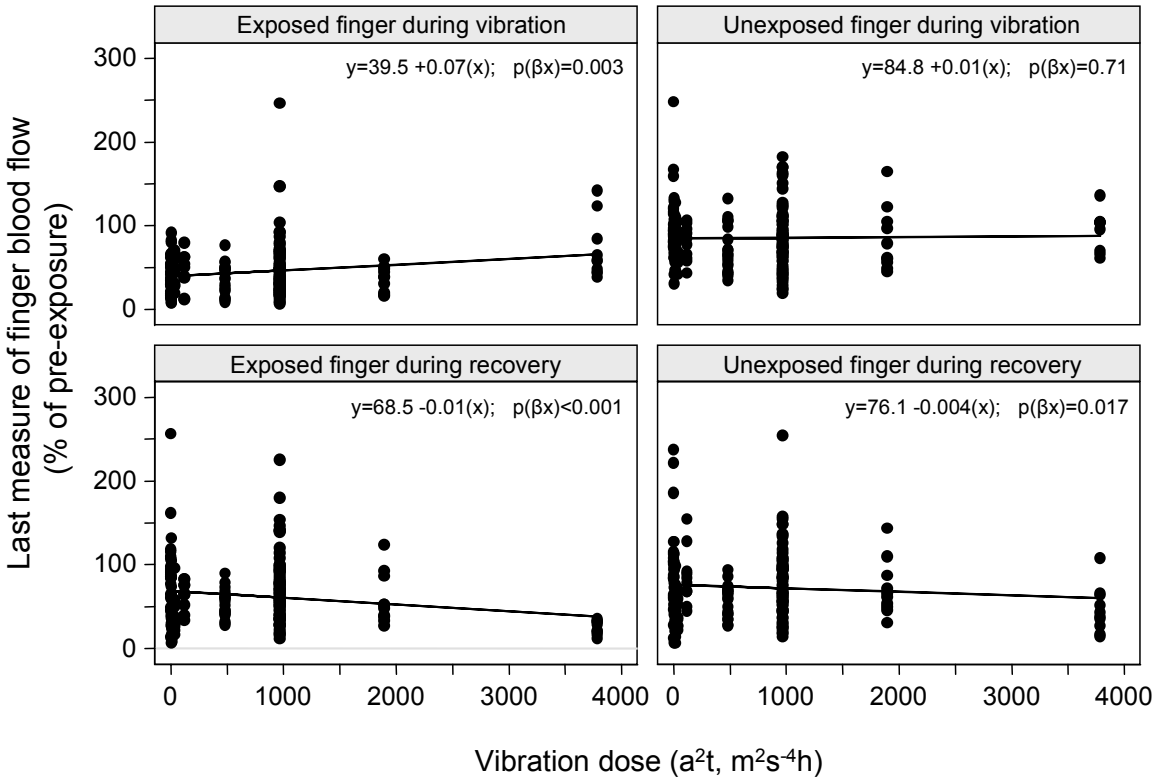

Figure 7. Percentage change of finger blood flow (FBF in % of pre-exposure) in the middle right finger (exposed finger) and the middle left finger (unexposed finger) during and after exposure to different magnitudes of vibration dose derived by combining acceleration magnitude with a power of 2 (a^2) and exposure time (t), (i.e. dose=a^2t in $m^2s^{-4}h$). Plotted symbols are mean values of the last measure of FBF (% of pre-exposure) during vibration exposure and a recovery period of 45 minutes.

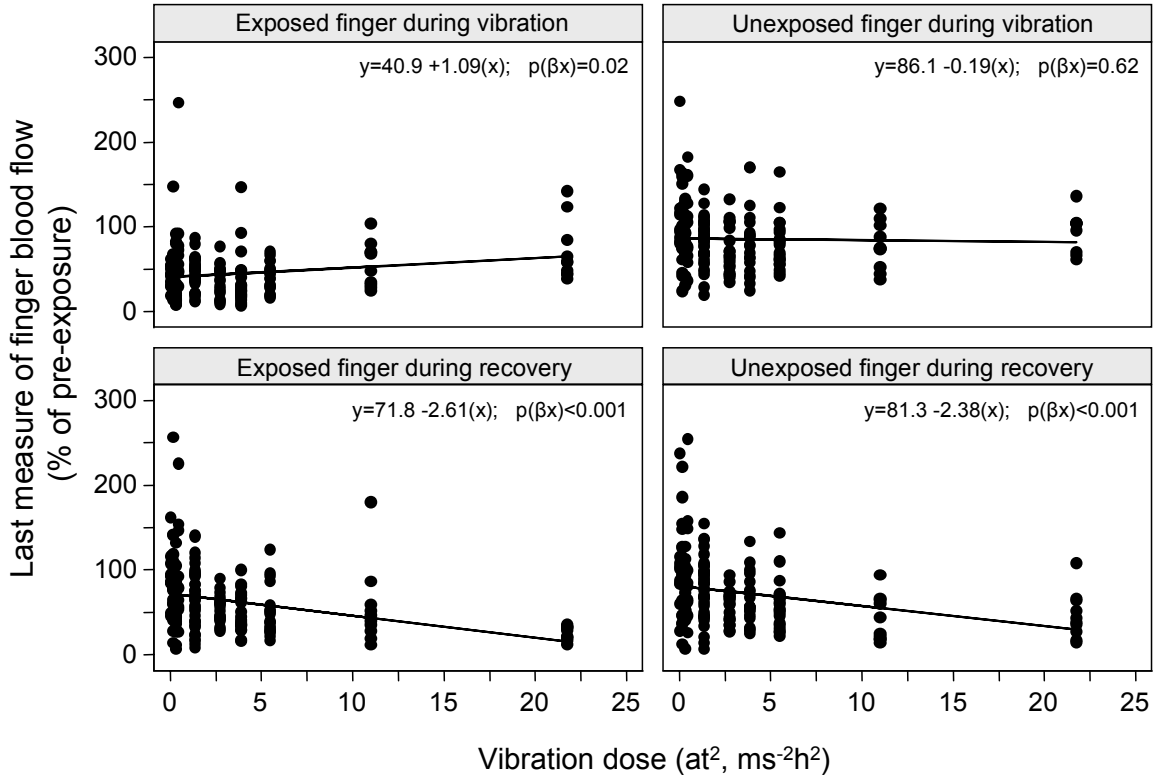

Figure 8. Percentage change of finger blood flow (FBF in % of pre-exposure) in the middle right finger (exposed finger) and the middle left finger (unexposed finger) during and after exposure to different magnitudes of vibration dose derived by combining acceleration magnitude (*a*) and exposure time with a power of 2 (t^2), (i.e. dose=at^2 in $ms^{-2}h^2$). Plotted symbols are mean values of the last measure of FBF (% of pre-exposure) during vibration exposure and a recovery period of 45 minutes.

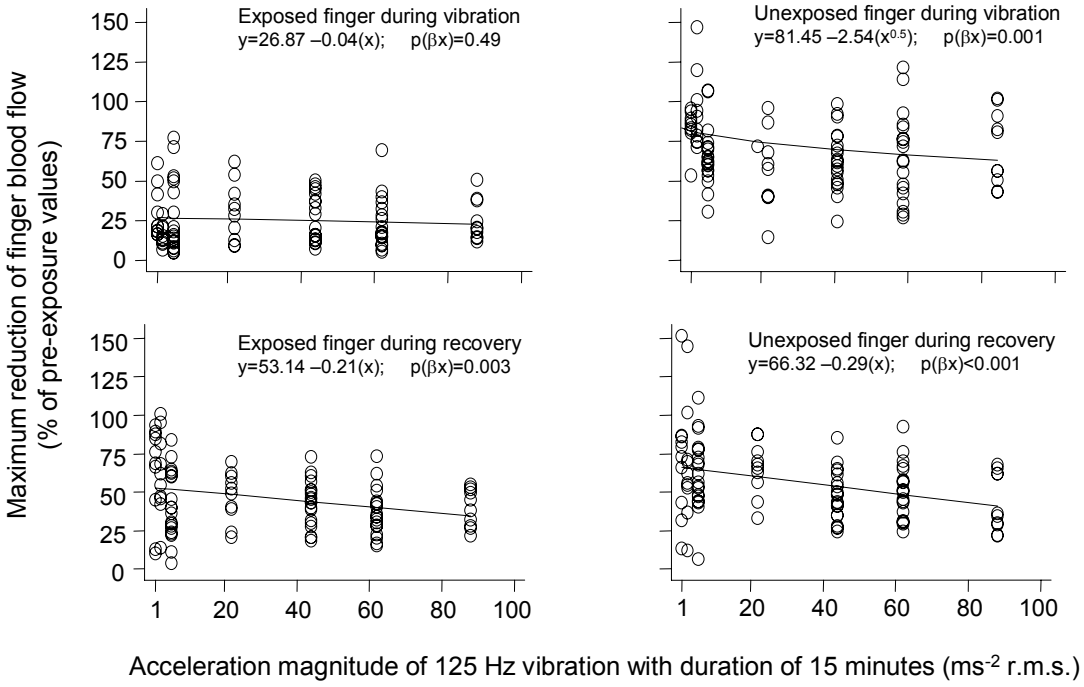

Figure 9. Percentage change of finger blood flow (FBF in % of pre-exposure) in the middle right finger (exposed finger) and the middle left finger (unexposed finger) during and after exposure to 125-Hz vibration with a duration of 15 minutes and different acceleration magnitudes (1 to 87 ms^{-2} r.m.s. unweighted). Plotted symbols are mean values of the maximum reduction of FBF (% of pre-exposure) during vibration exposure and a recovery period of 45 minutes.

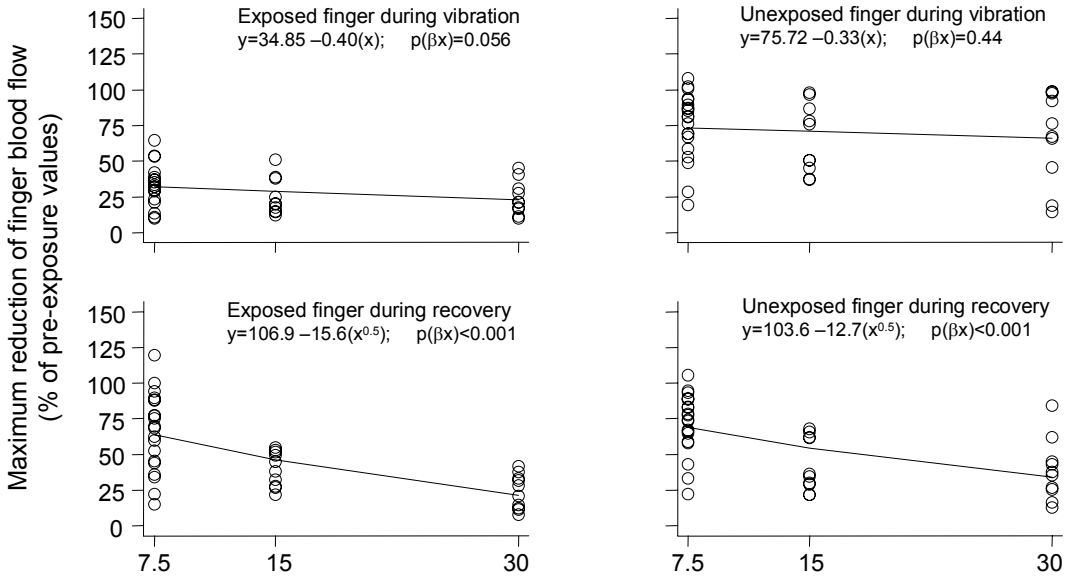

Figure 10. Percentage change of finger blood flow (FBF in % of pre-exposure) in the middle right finger (exposed finger) and the middle left finger (unexposed finger) during and after exposure to 125-Hz vibration with an acceleration magnitude of 87 ms^{-2} r.m.s. (unweighted) and different exposure durations (7.5 to 30 minutes). Plotted symbols are mean values of the maximum reduction of FBF (% of pre-exposure) during vibration exposure and a recovery period of 45 minutes.

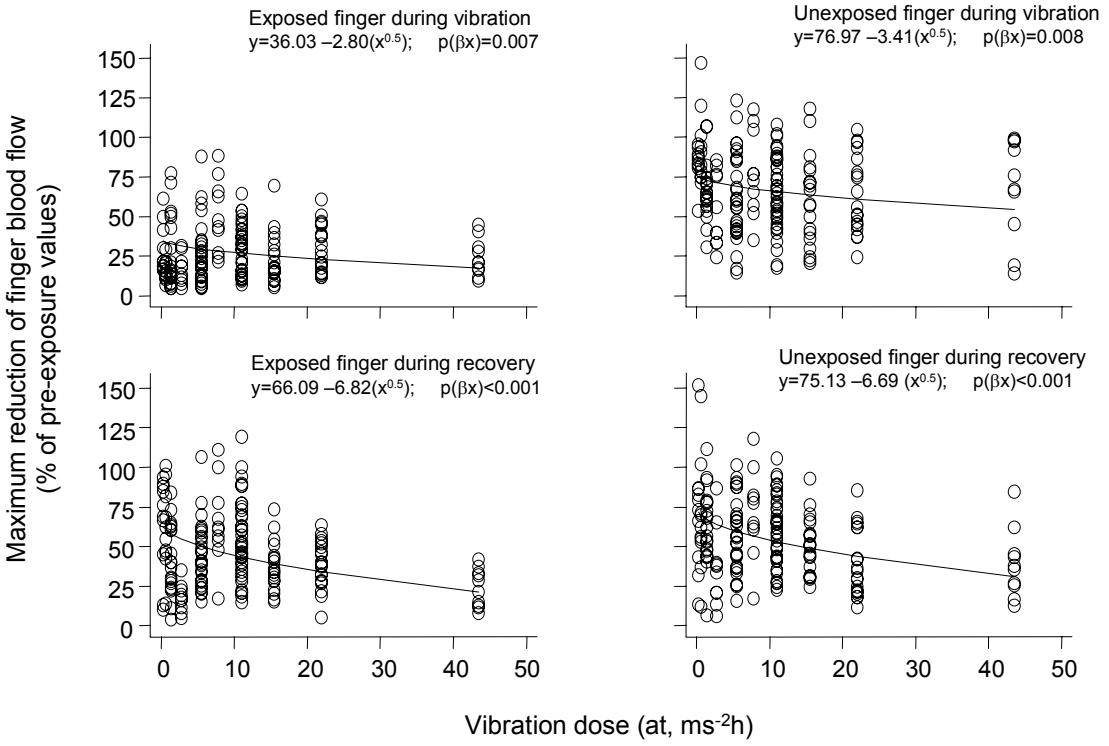

Figure 11. Percentage change of finger blood flow (FBF in % of pre-exposure) in the middle right finger (exposed finger) and the middle left finger (unexposed finger) during and after exposure to different magnitudes of vibration dose derived by combining acceleration magnitude (*a*) and exposure time (*t*), (i.e. dose=*at* in $ms^{-2}h$). Plotted symbols are mean values of the maximum reduction FBF (% of pre-exposure) during vibration exposure and a recovery period of 45 minutes.

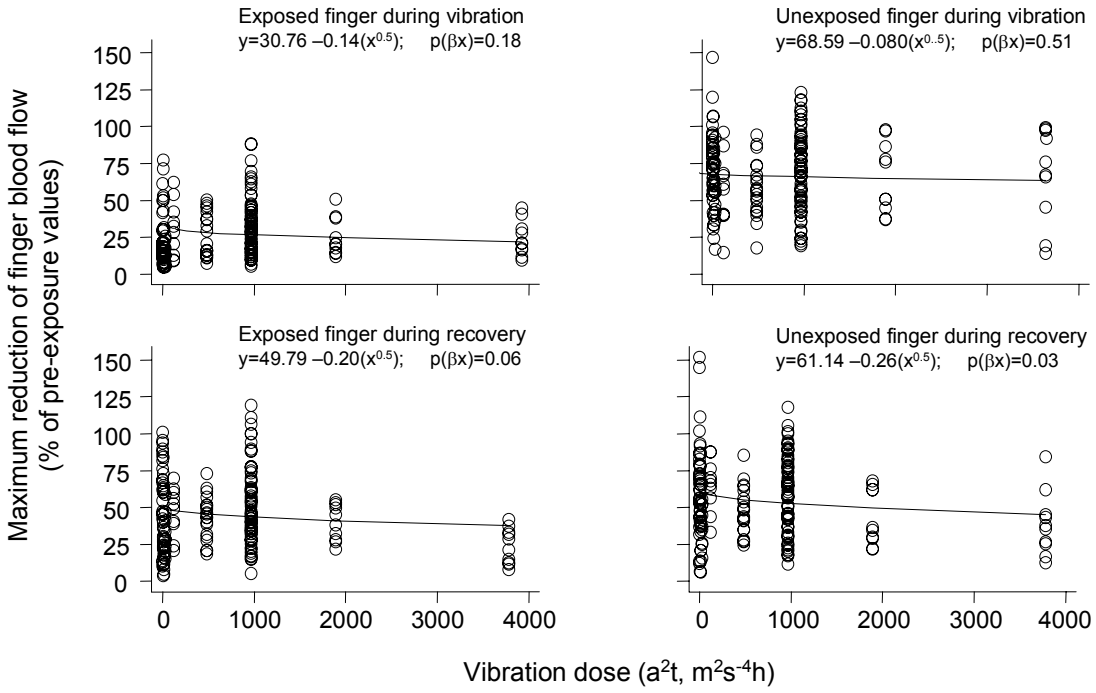

Figure 12. Percentage change of finger blood flow (FBF in % of pre-exposure) in the middle right finger (exposed finger) and the middle left finger (unexposed finger) during and after exposure to different magnitudes of vibration dose derived by combining acceleration magnitude with a power of 2 (a^2) and exposure time (t), (i.e. dose=a^2t in $m^2s^{-4}h$). Plotted symbols are mean values of the maximum reduction FBF (% of pre-exposure) during vibration exposure and a recovery period of 45 minutes.

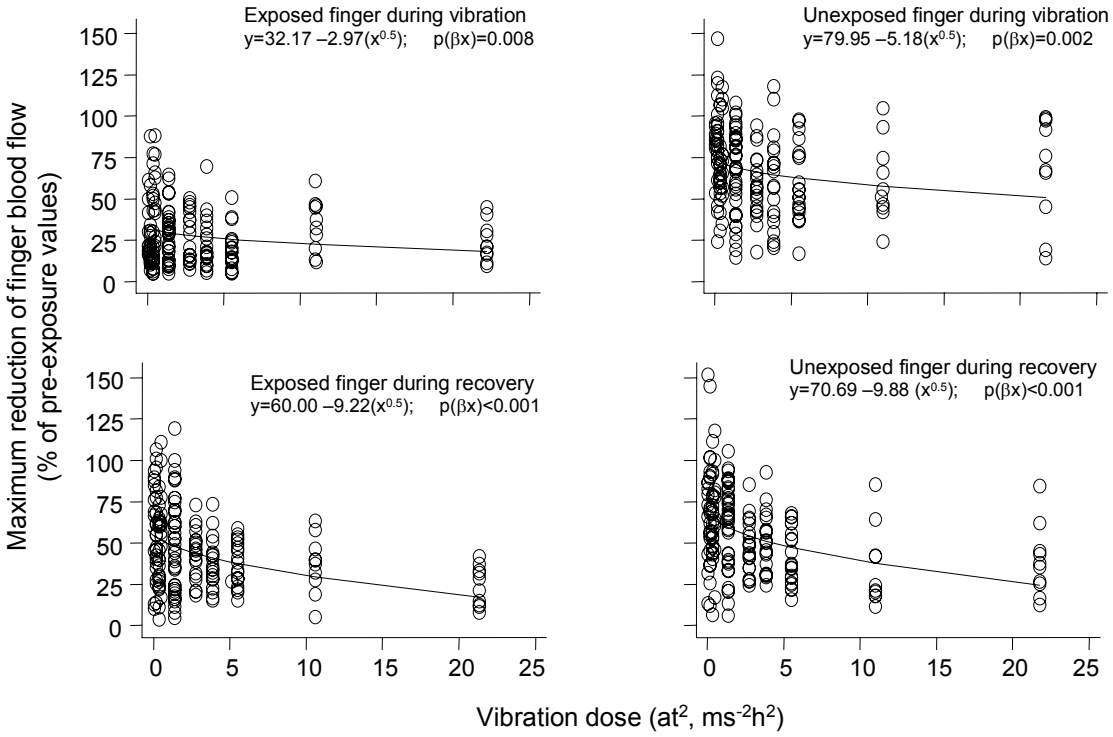

Figure 13. Percentage change of finger blood flow (FBF in % of pre-exposure) in the middle right finger (exposed finger) and the middle left finger (unexposed finger) during and after exposure to different magnitudes of vibration dose derived by combining acceleration magnitude (*a*) and exposure time with a power of 2 (t^2), (i.e. dose=at^2 in $ms^{-2}h^2$). Plotted symbols are mean values of the maximum reduction of FBF (% of pre-exposure) during vibration exposure and a recovery period of 45 minutes.

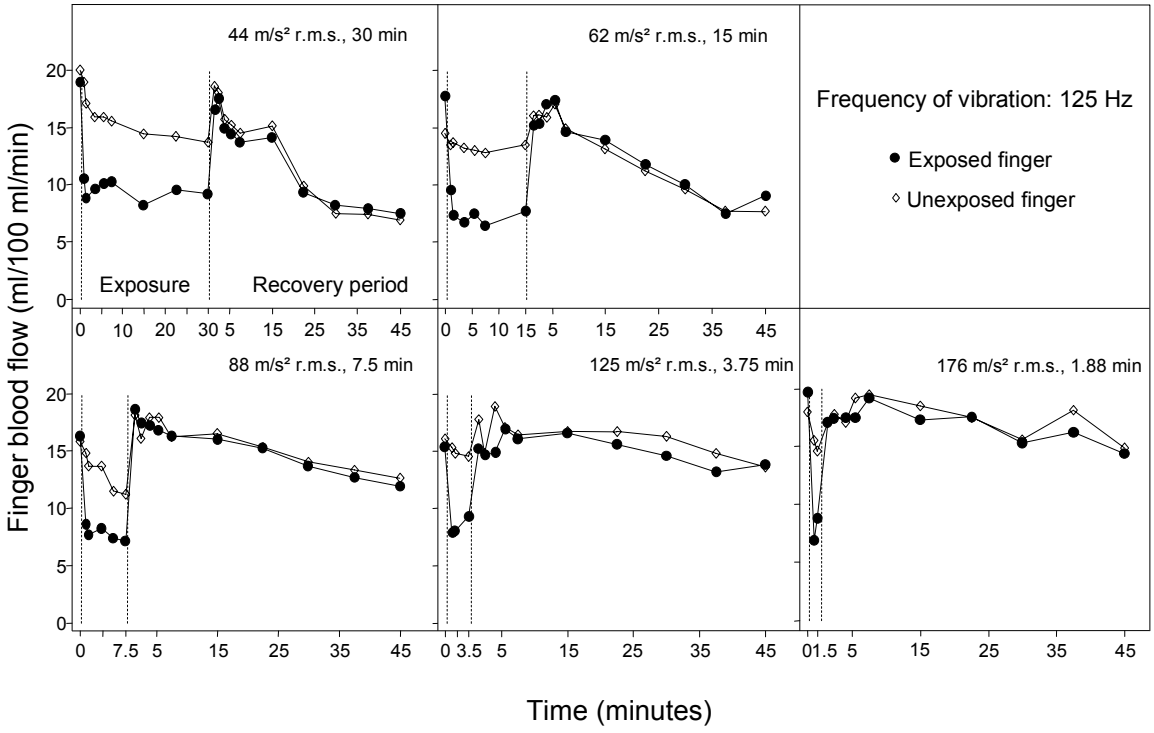

Figure 14. Mean values of finger blood flow (ml/100 ml/min) measured in ten healthy men before, during and after exposures to vibration with different combinations of acceleration magnitude and duration but with the same eight-hour "energy-equivalent" frequency-weighted acceleration magnitude (~1.4 m/s^2 r.m.s.) according to currents standards for hand-transmitted vibration.

Section 3

STUDY 2

ACUTE EFFECTS OF CONTINUOUS AND INTERMITTENT VIBRATION ON FINGER CIRCULATION

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3.1 Introduction

Occupational exposure to hand-transmitted vibration from powered tools or vibrating workpieces may give rise to vascular, neurological and musculoskeletal disorders in the upper limbs [11]. The complex of symptoms and signs of these disorders is called the hand-arm vibration syndrome, which is recognised as an occupational disease in many industrialised countries [5].

The approximate vibration conditions associated with the occurrence of the vascular disorder caused by exposure to hand-transmitted vibration, called vibration-induced white finger, have been reported in some studies. However, although many jobs involve intermittent exposures to vibration, epidemiological studies do not clearly indicate whether intermittency is beneficial or detrimental: it is not known whether the total exposure is the determining factor or whether some allowance should be made for breaks in exposure. Notwithstanding the uncertainty, it is widely suggested that working conditions characterised by continuous exposure to hand-transmitted vibration are more hazardous to worker health than conditions in which vibration exposure is interrupted with regular rest periods (i.e. periods without exposure to vibration).

The assumed importance of exposure intermittency is not new: a 1967 Work Hygiene Regulation in Czechoslovakia defined limits that varied according to the intermittency in exposures [6]. This influenced Draft International Standard 5349 (1979), which contained a procedure to allow for the benefits of intermittency in exposures; for example, the severity of a cumulative 4-hour total daily exposure to hand-transmitted vibration varied by a factor of four according to the durations of regular interruptions in exposures. According to the current International Standard, ISO 5349-1 [13], daily exposures are evaluated on the basis of the cumulative daily exposure and there is no allowance for intermittency. However, at item E.3.c in an annex dedicated to preventive measures to be adopted by persons responsible for occupational health and safety, this standard says: "*it is presumed that vibration hazards are reduced when continuous vibration exposure over long periods are avoided; therefore, work schedules should be arranged to include vibration-free periods*". In another annex it is suggested that "….*working conditions, methods of*

use of the tool and exposure duration patterns (including intermittency) should be reported". More recently, the Physical Agents Directive of the European Union states that if the exposure action value is exceeded, the introduction of *"work schedules with adequate rest periods"* should be considered [15].

The underlying assumption is that vibration-free rest periods could allow the human body tissues to recover from vibration-induced mechanical stress. At present, however, there is little experimental evidence and no epidemiological evidence that intermittency in exposures to hand-transmitted vibration has a beneficial effect, either to prevent the onset of vibration injuries or to reduce the occurrence of vibration-induced disorders [8, 14].

The aim of this study was to compare the response of finger circulation to acute exposures to continuous and intermittent vibration. All exposures had the same frequency of vibration and the same energy-equivalent acceleration magnitude: they would have equal risk according to current standards if they were to occur routinely in an occupation. A vibration frequency of 125 Hz was used because previous experimental studies have shown that this frequency induces greater changes in finger circulation than some lower or higher frequencies [3, 12, 16]. Finger blood flow was measured simultaneously in four fingers of healthy men (two ipsilateral and two contralateral to vibration exposure), using a newly developed multi-channel, computer-controlled, strain-gauge plethysmograph.

3.2 Subjects and Methods

3.2.1 SUBJECTS

Ten healthy male volunteers gave written informed consent to participate in the investigation. All subjects were students or office workers with no history of regular use of hand-held vibrating tools in occupational or leisure activities. Eight subjects were non-smokers. None of them reported cardiovascular or neurological disorders, connective tissue diseases, injuries to the upper extremities or a family history of Raynaud's phenomenon. The mean age of the subjects was 29 (range 23 – 46; SD 7) years, their mean stature was 181 (range 170 – 195; SD 7) cm and their mean weight was 77 (range 62 – 107; SD 13) kg. Finger dimensions were measured with

vernier callipers to a precision of 0.5 mm. Finger volume was calculated from that of a cylinder formed from an ellipse based on the dimensions of the proximal interphalangeal joint and the length of the finger. The mean (SD) volume of the middle right finger was 21.2 (3.7) cm^3, the middle left finger was 19.7 (3.9) cm^3, the little right finger was 11.4 (2.3) cm^3 and the little left finger was 10.9 (2.1) cm^3.

3.2.2 MEASURES OF FINGER CIRCULATION

Finger blood flow (FBF) was measured in the middle and little fingers of both the right and the left hand. Mercury-in-silastic strain gauges were placed around the distal phalanx at the base of the nails and plastic pressure cuffs for air inflation (2.4 □.9 cm) were fixed around the proximal phalanges and secured with a Velcro strip. The pressure cuffs and strain gauges were connected to a 5-channel plethysmograph (*HVLab*, ISVR, University of Southampton).

The FBF was measured using a venous occlusion technique: the pressure cuffs were inflated to a pressure of 60 mmHg and the increases in finger volumes were detected by means of strain gauges according to the criteria given by Greenfield et al [9]. Three to five plethysmographic recordings of FBF were made for each digit during each measurement, and the mean values calculated. The FBF measurements were expressed as ml/100ml/min.

Brachial systolic and diastolic blood pressures were measured in the upper right arm by an auscultatory technique using a standard rubber cuff (12 x 23 cm).

Finger skin temperature (FST) was measured using a k-type thermocouple connected to an *HVLab* Thermal Aesthesiometer so as to measure temperature with an accuracy of ±0.2°C. The thermocouple was taped to the dorsal surface of the medial phalanx of the right middle finger using porous surgical tape.

The room temperature was measured by a mercury-in-glass thermometer.

3.2.3 EXPERIMENTAL PROCEDURE

The experiment was performed in a room with a mean (SD) temperature of 26.5 (0.9)°C. Subjects were requested to avoid caffeine consumption for two hours and tobacco and alcohol for 12 hours prior to testing.

The subjects lay supine throughout the investigation with their hands resting on platforms alongside the body at about the level of the heart. After a period of acclimatisation of about 15 minutes, FBF was measured in the middle and little fingers of both hands; FST was measured in the middle right finger. After the pre-exposure measurements had been obtained, the subjects were asked to apply a downward force of 10 N with their right hand on a horizontal wooden platform that was mounted on an electrodynamic vibrator (VP4, Derritron). The signal from a Tedea Huntleigh force cell mounted between the platform and the shaker was used to provide visual feedback on a meter for the control of downward force. The index, middle and ring fingers of the right hand were in contact with the wooden platform and the little finger was independently supported at the same height. The arrangement for controlling contact force and for generating and monitoring the vibration has been described elsewhere [4].

Sinusoidal vibration was produced in the vertical direction at a frequency of 125 Hz at a root-mean-square (r.m.s.) acceleration magnitude of 44 ms^{-2} (unweighted), corresponding to a frequency-weighted acceleration of 5.6 ms^{-2} r.m.s. The total duration of vibration exposure on each occasion was 30 minutes, divided into the following intermittent vibration exposure periods and rest periods (Table 1):

(i) 1 period of 30-minute continuous vibration; 45 minutes recovery

(ii) 2 periods of 15 minutes, separated by a 15-minute period with no vibration; 45 minutes recovery

(iii) 4 periods of 7.5 minutes, separated by 7.5-minute periods with no vibration; 45 minutes recovery

(iv) 8 periods of 3.75 minutes, separated by 3.75-minute periods with no vibration; 45 minutes recovery

(v) 16 periods of 1.88 minutes, separated by 1.88-minute periods with no vibration; 45 minutes recovery.

All five exposures correspond to an 8-hour energy-equivalent frequency-weighted acceleration magnitude of 1.4 ms^{-2} r.m.s. according to International Standard ISO 5349-1 [13].

The measurements of FBF were made in the exposed (i.e. right) middle finger and in the unexposed right little finger, left middle finger and left little finger immediately before vibration exposure, throughout the vibration exposure period, and for 45 minutes following exposure.

During vibration exposures in conditions (i) to (iv), measures of finger circulation were obtained 0.5 minutes following the start of vibration and at 2-minute intervals during vibration. Similarly, during rest periods, measures of finger circulation were obtained 0.5 minute following the cessation of vibration and at 2-minute intervals during the rest period. In condition (v), with 16 periods of 1.88 minutes of exposure and rest, measurements were obtained at 1-minute intervals, following the start of vibration.

During recovery, measures were obtained 0.5 minutes following the cessation of vibration and at 2-minute intervals from the cessation of vibration until the end of the recovery period.

Brachial blood pressures were measured at the beginning and at the end of each experimental session.

Some previous studies have found that measures of finger circulation (FST and FBF) do not change when applying a similar static force with a similar posture to that used in this experiment [1, 3]. For this reason, the present study did not include a static condition.

Each of the ten subjects experienced all five experimental conditions on five separate days. Across the subject group, the five experimental conditions were presented in a balanced order. The experimental sessions lasted approximately 2 hours. All sessions were completed within a three-week period.

The study was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton (UK).

3.2.4 STATISTICAL METHODS

Data analysis was performed using the software package Stata (version 7.0 SE). The data were summarised with the mean as a measure of central tendency and the standard deviation (SD) or the standard error of mean as measures of dispersion.

The difference between paired means was tested by the Student's *t* test.

Repeated measures analysis of variance (ANOVA) was used to test the hypothesis of no difference in the vascular responses in different exposure conditions ("treatments"). To control for the effect of covariates on the response variables, repeated measures analysis of covariance (ANCOVA) was also used. When the compound symmetry assumption (that is, the measures have the same variance and the correlations between each pair of repeated measures are equal) was violated, a conservative test of the repeated measures factor was used by reducing the degrees of freedom of the *F* ratio (Greenhouse-Geisser method) [10]. The 95% Bonferroni confidence intervals for pairwise mean comparisons of the response by time were used when the probability value for the *F* test of repeated measures ANOVA was $p<0.05$ (two-sided).

The relation between continuous variables with repeated measures was assessed by the generalised estimating equations (GEE) approach to repeated measures data sets in order to account for the within-subject correlation [7].

3.3 Results

3.3.1 FINGER CIRCULATION BEFORE VIBRATION EXPOSURES

The vascular measurements before exposure to vibration showed no changes in either FBF or FST in either the exposed or the unexposed fingers across the five experimental sessions. No differences in the pre-exposure measures of digital circulation were found between the middle right and middle left finger or between the

little right and little left finger within any session. Table 2 reports the baseline measures of finger blood flow before exposures to continuous and intermittent vibration.

Brachial systolic and diastolic arterial pressures measured before exposure did not change significantly within subjects across sessions (range of values across subjects and sessions: 115/70 – 130/80 mmHg). No difference was observed for the brachial arterial blood pressures measured at the beginning and the end of the five sessions.

In pre-exposure conditions, analysis of repeated measures by the GEE method showed that in the middle right finger FBF was positively related to FST ($p<0.01$). For all fingers, the FBF showed a positive, even though not statistically significant, relation to room temperature ($p=0.15 – 0.27$)

Neither age nor the volume of the fingers was correlated with the baseline measures of digital circulation.

Repeated measures ANOVA revealed no significant difference in the air temperature of the laboratory across the five experimental sessions, ranges of mean (SD) values being 26.6 (0.3) – 26.8 (0.2)°C.

3.3.2 Finger circulation during exposure to continuous or intermittent vibration

Over the five experimental sessions, the GEE analysis of repeated measures showed no significant changes in the FST of the middle right (exposed) finger during either continuous or intermittent exposures to vibration (results not shown).

Acute exposure to vertical vibration with a frequency of 125 Hz and an unweighted acceleration magnitude of 44 ms^{-2} r.m.s. provoked an immediate reduction of FBF in the middle right (exposed) finger at the beginning of each exposure period for all experimental conditions (Figures 1 to 5).

During the 30-minute exposure to continuous vibration (Figure 1), the decrease of FBF in the exposed finger was persistent over the whole exposure period and the percentage change in FBF at each measurement time was significant when compared with the pre-exposure FBF. After control for age, finger dimension and

room temperature, repeated measures ANCOVA showed that the reduction of FBF in the exposed finger was significantly stronger than that measured in both the unexposed ipsilateral finger and the unexposed contralateral fingers ($p<0.001$). The percentage change in the FBF of the unexposed right little finger was greater than in the contralateral (unexposed) left fingers ($p<0.001$). Compared with the measurements before exposure, no significant change was observed for the FBF in the contralateral (unexposed) fingers throughout the 30-minute vibration exposure period. There was no difference in the changes of FBF between the two contralateral fingers.

Finger circulation during intermittent vibration (44 ms^{-2} r.m.s. at 125 Hz) with durations of 15, 7.5, 3.75 and 1.88 minutes (spaced out by equal vibration-free rest periods), all with the same 8-hour energy-equivalent acceleration magnitude of 1.4 ms^{-2} r.m.s., are shown in Figures 2 to 5. Overall, the change in the FBF of the middle right (exposed) finger exhibited a similar pattern across all experimental sessions: a rapid decrease of FBF during vibration exposures followed by a prompt restoration of FBF during the vibration-free rest periods. As during the 30-minute exposure to continuous vibration, the reduction of FBF in the ipsilateral (right) fingers was significantly stronger than in the contralateral (unexposed left) fingers ($p<0.001$) and the percentage changes of FBF in the middle right (exposed) finger was greater than in the little right (unexposed) finger ($p<0.001$). During each period of intermittent vibration exposure, FBF in the ipsilateral fingers decreased significantly compared with both the pre-exposure FBF and the FBF during the vibration-free rest periods ($0.001<p<0.05$). Within both right (ipsilateral) fingers, there was no significant difference in the degree of the vasoconstrictor response within each vibration exposure period.

During intermittent exposures, immediately after the end of each vibration stimulus, there was an increase in the FBF of the right (ipsilateral) fingers. This vasodilation was observed more frequently in the middle right (exposed) finger. The FBF in both ipsilateral fingers during the vibration-free rest periods immediately after the end of the vibration stimuli was not significantly different from the pre-exposure values.

In the contralateral (unexposed left) fingers, there was no significant change in the FBF over the four sessions with intermittent vibration exposure when compared with

the blood flow measured before exposure, neither during vibration nor during the rest periods.

3.3.3 Finger circulation after exposure to continuous or intermittent vibration

During the recovery period following exposures to either continuous or intermittent vibration, repeated measures ANCOVA revealed no significant treatment-by-time interaction for either FST or FBF across the five experimental sessions. As a result, the overall patterns of the changes in FST and FBF could be compared over the whole recovery period across the various exposure conditions.

In the middle right (exposed) finger, FST during recovery did not change significantly across the experimental sessions (results not shown).

Within each finger, the patterns of the percentage change of FBF during recovery were not different across the five exposure conditions ($p=0.49$-0.97). Likewise, within each exposure condition there was no difference in the change of FBF during recovery across fingers, with the exception of the experimental condition with 30-minute exposure to continuous vibration. With continuous vibration, a small, although significant, reduction in the FBF of both ipsilateral (right) fingers was observed compared with that measured in the contralateral (left) fingers ($p<0.05$). Repeated measures ANCOVA showed that the difference between the ipsilateral and contralateral fingers was mainly due to a greater decrease in the FBF of the ipsilateral fingers during the second half of the recovery period.

When compared with the pre-exposure measures of FBF, the Bonferroni test revealed a significant decrease in the FBF of the middle right (exposed) finger during the last 15 minutes of the recovery period after the end of 30-minute exposure to continuous vibration ($p<0.02$). No significant differences compared to the baseline FBF were observed for the other fingers after exposure to any other condition (continuous or intermittent vibration exposure). Nevertheless, the mean values of FBF showed some evidence of vasoconstriction after exposure to vibration, as found in our previous investigations [1, 2].

3.4 Discussion

3.4.1 Comparison with previous studies

Our previous studies have consistently found that vibration of a finger produces vasoconstriction during exposure, followed by an immediate vasodilation and then the onset of a period of vasoconstriction lasting 30 minutes or more during a recovery period. The strength of vasoconstriction during exposure depends on the vibration frequency and the vibration magnitude [2, 3]. The strength and duration of the vasoconstriction following exposure depends on the duration of vibration exposure in addition to the vibration frequency and vibration magnitude [1]. The previous studies have shown similar, although somewhat reduced, effects on an unexposed contralateral finger.

With 30-minute continuous vibration used in the current study, the patterns of the response of FBF in both the exposed right finger and the unexposed left fingers are similar to those obtained with the same stimulus (44 ms^{-2} r.m.s. at 125 Hz for 30 minutes) in a previous study [4]. However, a clear but weak reduction of FBF in the unexposed contralateral finger seen in the previous study is not observed in the results of the current study. In the previous studies there were no measurements on an unexposed ipsilateral finger.

In our series of experiments, we have not previously measured FBF response to intermittent vibration. Egan et al [8] investigated the effects of three 2-minute exposures to vibration from a pneumatic chisel, with each period of vibration separated by a 10-minute rest without vibration. In exposed and unexposed fingers, vibration reduced the blood flow by an amount that did not appear to change greatly between the three periods of vibration: there was a downward trend in blood flow over the three periods but a similar trend was observed during a control condition without vibration. Luo et al [14] measured finger blood flow over three 5-minute periods of vibration separated by 5-minute rests. They reported a downward trend in the finger blood flow over the three periods of vibration in the unexposed hand but not the exposed hand. The present study found no evidence of a significant change in the degree of vascular response to vibration over the various intermittent exposures in either the exposed or the unexposed hand.

3.4.2 Finger circulation during exposure to continuous or intermittent vibration

In the exposed (right) finger, in all five conditions there were significant reductions in FBF during vibration. There was no significant change in the reduction of FBF during the 30-minute continuous vibration over the whole exposure period. Also, the overall mean change in the percentage FBF during exposure did not differ between conditions or between repeated exposures during the four intermittent conditions. This suggests that neither the accumulation of exposure (i.e. dose) nor periods of rest (varying from 1.88 to 15 minutes) affected the FBF response to vibration exposure. This may indicate that, with the magnitude, frequency and durations of vibration studied here, the reduction of FBF was primarily a direct effect, with little cumulative influence. This does not exclude a cumulative effect, or some compensatory mechanism, coming into play in some circumstances, as may be evident in a previous study where there was evidence of reduced vasoconstriction after about 15 minutes of vibration [1]. Any such changes in the present study were not significant, but the present study employed a lower magnitude of vibration (44 ms^{-2} r.m.s. compared with 87 ms^{-2} r.m.s. in the previous study).

In the ipsilateral unexposed right finger there was a significant reduction of FBF during vibration over the 30-minute continuous exposure and during the four conditions of intermittent vibration. However, in this experiment there were no reductions in either of the contralateral (unexposed left) fingers. The absence of vasoconstriction in fingers on the contralateral hand differs from our previous studies and this may be due, at least partially, to the lower vibration magnitude used in the present study [1].

3.4.3 Finger circulation after exposure to continuous or intermittent vibration

As in previous studies, there was evidence of a reduction in FBF following vibration exposure. However this was only significant in the exposed (right) finger after exposure to the 30-minute continuous vibration. In the present experiment, the apparently smaller after-effect in the unexposed contralateral fingers is consistent with the absence of significant vasoconstriction during exposure in these fingers. In previous experiments, where there has been vasoconstriction in the unexposed fingers during exposure to vibration, there has also been evidence of

vasoconstriction following exposure [1, 2]. The absence of significant vasoconstriction in the contralateral fingers during or following intermittent vibration could indicate that effects of intermittent vibration were less severe than the effects of continuous exposure.

The effects following the end of exposure to vibration in this experiment were less with intermittent exposures, but it should not be forgotten that there were also periods without vibration during the exposure period. The responses during these periods (a cumulative total of 15 minutes) need to be considered when assessing the overall impact of the five different cumulative 30-minute exposures. During these 'rest' periods there was no reduction in the blood flow. So, if the duration and extent of vasoconstriction is an indicator of the cumulative risk of damage caused by an exposure to hand-transmitted vibration, the present results may indicate less risk with intermittent exposures.

3.4.4 Comparison with current standards

Current standards and guides for the evaluation and assessment of exposures to hand-transmitted vibration disregard the influence of periods without vibration and merely accumulate the total exposure duration over a day, regardless of whether it arises from one long exposure or many shorter exposures.

The reduction in FBF observed during the vibration exposure in the present study did not differ between the continuous and intermittent exposures, as implied by the evaluation method in current standards [13]. However, although these standards may be correct in not distinguishing between intermittent and continuous exposures they are not good at predicting how the response of FBF to vibration exposure depends on the magnitude, frequency or duration of exposures [1, 2, 3].

The current results indicate less after-effect of vibration exposure when the vibration included rest periods, suggesting that breaks in exposure may be beneficial. This is inconsistent with the evaluation methods in current standards. However, the findings of this study seem to be consistent with the general recommendation of current guides suggesting that rest periods may be beneficial.

3.5 Conclusion

The reduction of blood flow occurring in a finger exposed to vibration was similar during continuous and intermittent exposures. However, the decrease in FBF was less following exposure to intermittent vibration. The results suggest that exposures to intermittent vibration might be less hazardous than exposure to the same vibration without breaks in exposure. Although some evidence from this study is consistent with intermittent vibration having a less severe effect than continuous vibration, this evidence is not yet conclusive.

The preliminary results obtained from this study require extension to more severe exposures: greater vibration magnitudes and longer exposures similar to those associated with a known risk of vascular disorders (e.g. vibration-induced white finger) in many occupations.

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Table 1. Conditions of exposure to continuous and intermittent vibration used in this study (the frequency-weighted root-mean-square (r.m.s.) acceleration magnitude of vibration and the 8-hour energy-equivalent frequency-weighted acceleration magnitude (*A*(8)) are calculated according to International Standard ISO 5349-1).

Vibration frequency (Hz)	Unweighted acceleration magnitude (ms^{-2} r.m.s.)	Frequency-weighted acceleration magnitude (ms^{-2} r.m.s.)	Exposure duration (minutes)	Number of vibration exposures	Number of rest periods	*A*(8) (ms^{-2} r.m.s.)
125	44	5.6	30	1	0	1.4
125	44	5.6	15	2	1	1.4
125	44	5.6	7.5	4	3	1.4
125	44	5.6	3.75	8	7	1.4
125	44	5.6	1.88	16	15	1.4

Table 2. Baseline measures of finger blood flow (ml/100 ml/min) before exposures to continuous and intermittent vibration. Data are given as means (standard errors of mean).

Finger	Conditions of exposure to continuous and intermittent vibration (number of exposures × time)				
	1 × 30 minutes	2 × 15 minutes	4 × 7.5 minutes	8 × 3.75 minutes	16 × 1.88 minutes
3rd right finger (exposed)	35.7 (3.1)	33.0 (4.1)	33.6 (4.7)	37.2 (3.6)	36.1 (4.2)
5th right finger (unexposed)	26.4 (1.9)	28.3 (3.6)	30.5 (5.3)	27.4 (4.4)	29.6 (3.2)
3rd left finger (unexposed)	33.6 (6.7)	34.0 (6.2)	34.2 (4.5)	38.5 (5.2)	37.3 (3.2)
5th left finger (unexposed)	23.2 (2.9)	26.4 (5.0)	31.4 (3.6)	27.9 (4.6)	28.6 (3.8)

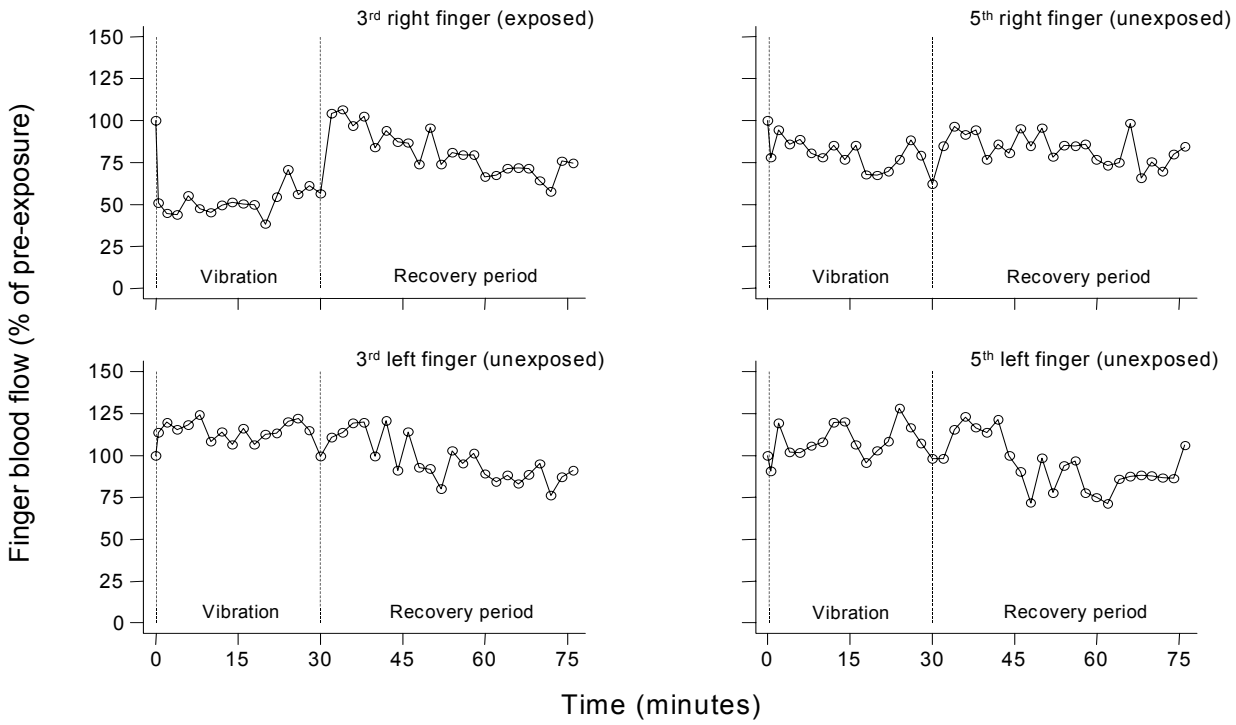

Figure 1. Mean percentage changes in the finger blood flow of 10 healthy men during and after exposure to 30-minute continuous vibration with a frequency of 125 Hz, an unweighted root-mean-square (r.m.s.) acceleration magnitude of 44 ms^{-2}, and an 8-hour energy-equivalent frequency-weighted acceleration magnitude of 1.4 ms^{-2} r.m.s. according to International Standard ISO 5349-1 (2001).

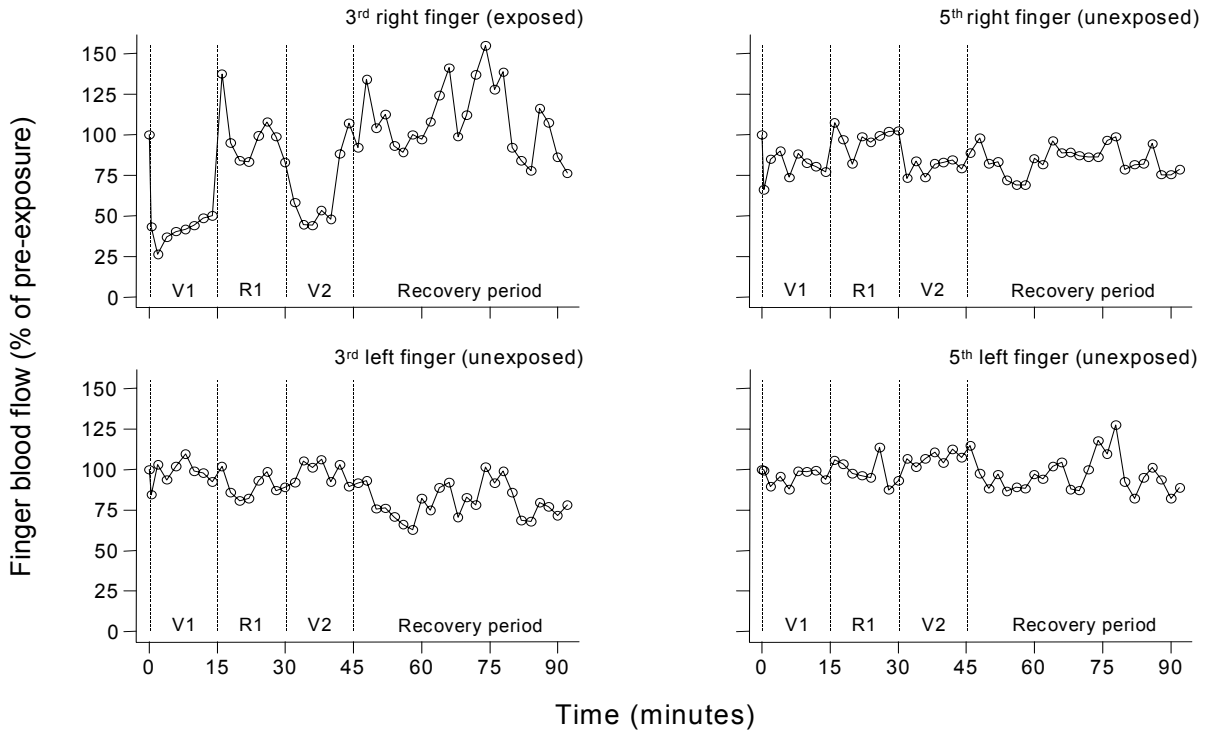

Figure 2. Mean percentage changes in the finger blood flow of 10 healthy men during and after exposure to intermittent vibration [2 vibration periods of 15 minutes (V), separated by a 15-minute period with no vibration (R)] with a frequency of 125 Hz, an unweighted root-mean-square (r.m.s.) acceleration magnitude of 44 ms^{-2}, and an 8-hour energy-equivalent frequency-weighted acceleration magnitude of 1.4 ms^{-2} r.m.s. according to International Standard ISO 5349-1 (2001).

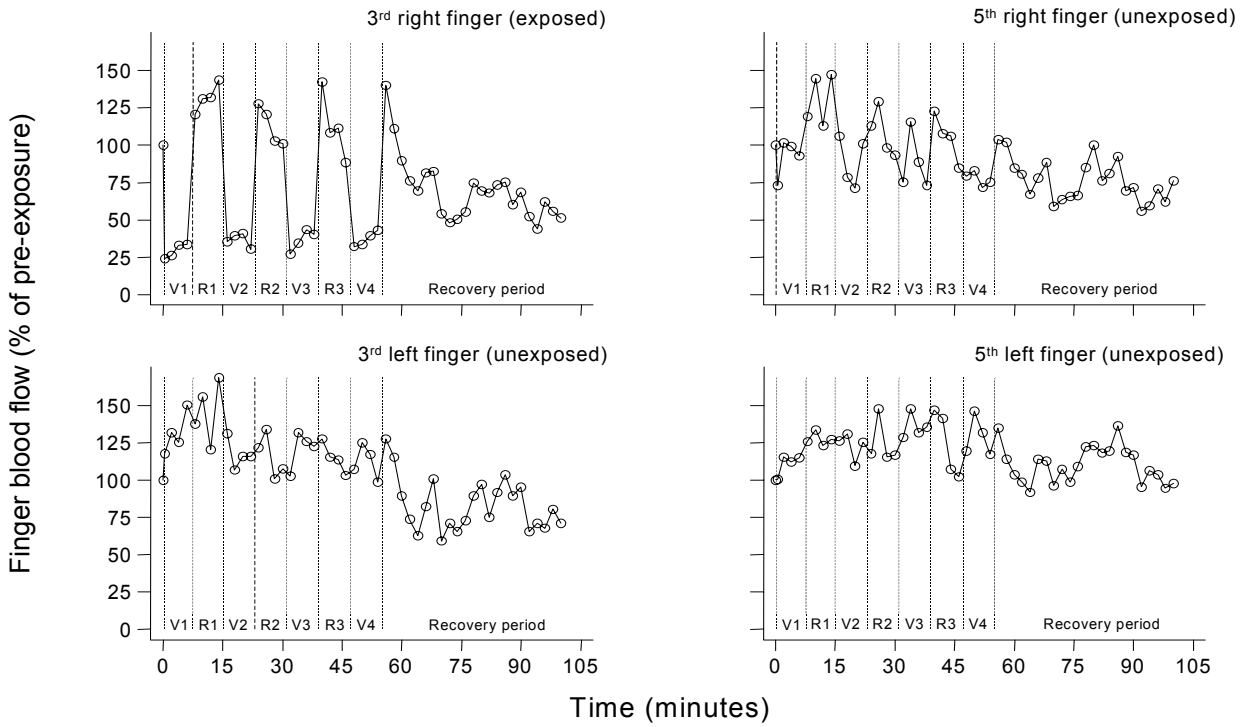

Figure 3. Mean percentage changes in the finger blood flow of 10 healthy men during and after exposure to intermittent vibration [4 vibration periods of 7.5 minutes (V), separated by 7.5-minute periods with no vibration (R)] with a frequency of 125 Hz, an unweighted root-mean-square (r.m.s.) acceleration magnitude of 44 ms^{-2}, and an 8-hour energy-equivalent frequency-weighted acceleration magnitude of 1.4 ms^{-2} r.m.s. according to International Standard ISO 5349-1 (2001).

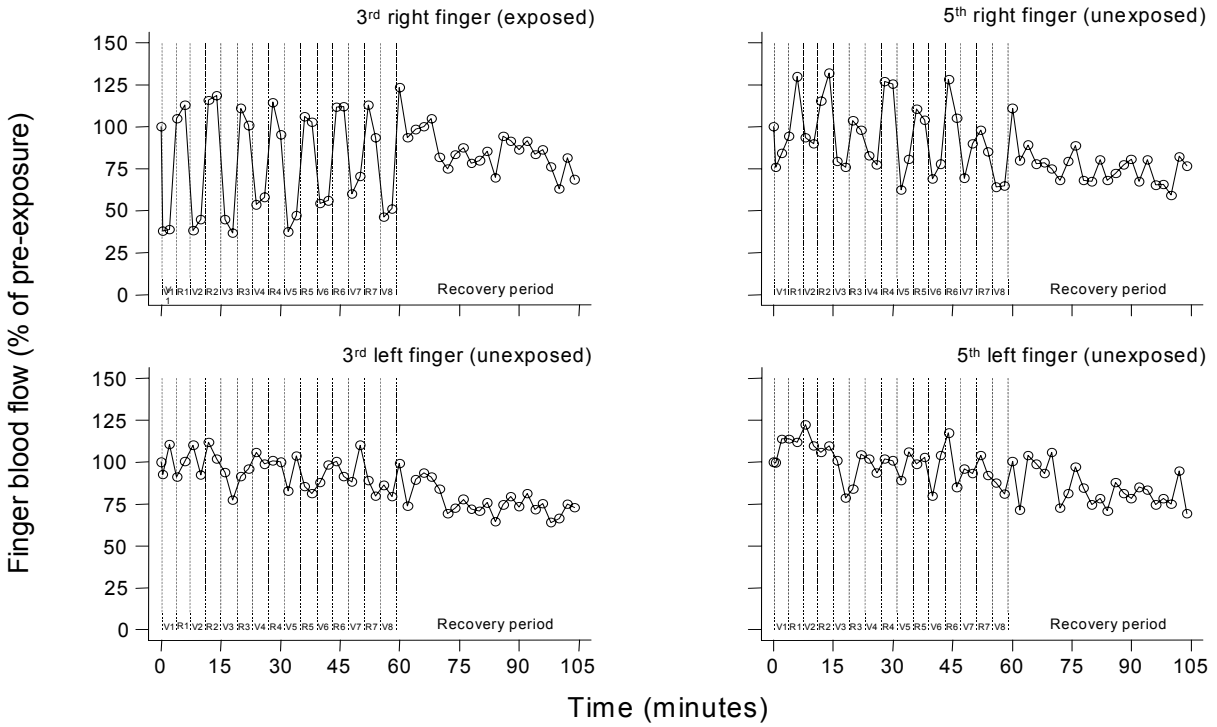

Figure 4. Mean percentage changes in the finger blood flow of 10 healthy men during and after exposure to intermittent vibration [8 vibration periods of 3.75 minutes (V), separated by 3.75-minute periods with no vibration (R)] with a frequency of 125 Hz, an unweighted root-mean-square (r.m.s.) acceleration magnitude of 44 ms^{-2}, and an 8-hour energy-equivalent frequency-weighted acceleration magnitude of 1.4 ms^{-2} r.m.s. according to International Standard ISO 5349-1 (2001).

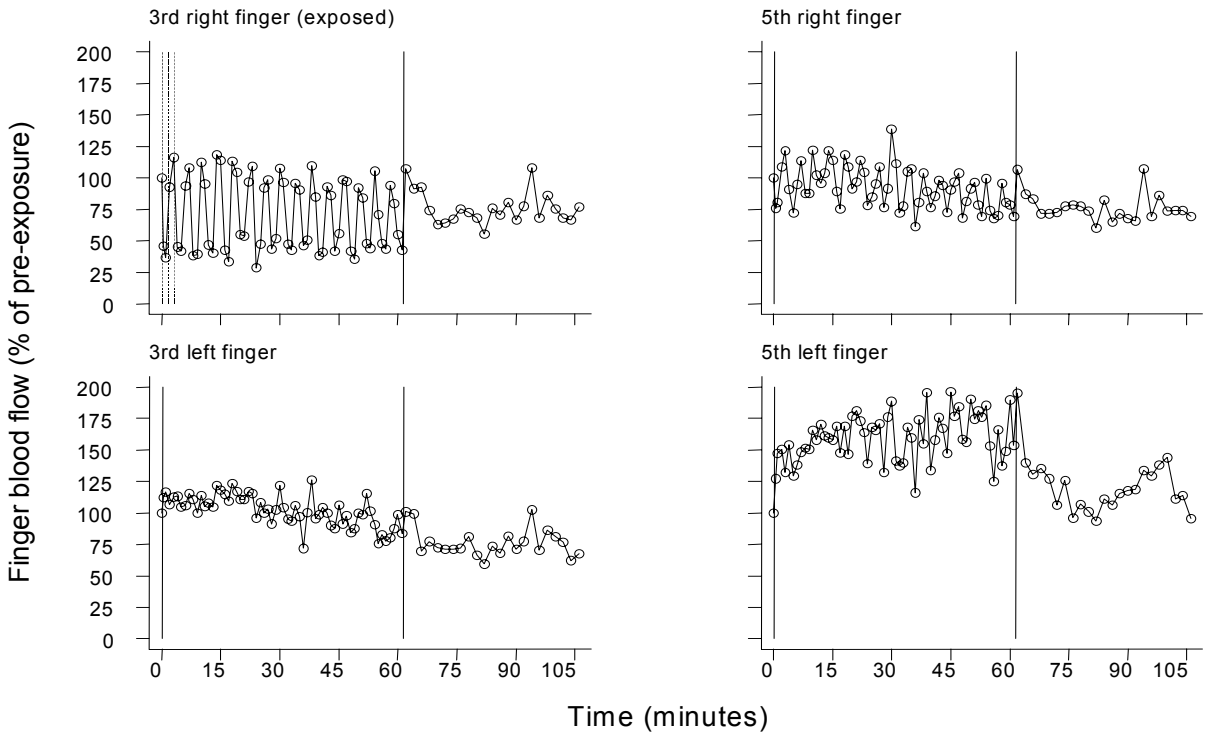

Figure 5. Mean percentage changes in the finger blood flow of 10 healthy men during and after exposure to intermittent vibration [16 vibration periods of 1.88 minutes (V), separated by 1.88-minute periods with no vibration (R)] with a frequency of 125 Hz, an unweighted root-mean-square (r.m.s.) acceleration magnitude of 44 ms^{-2}, and an 8-hour energy-equivalent frequency-weighted acceleration magnitude of 1.4 ms^{-2} r.m.s. according to International Standard ISO 5349-1 (2001).

Section 4

STUDY 3

Acute effects of force and vibration on finger blood flow

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4.1 Introduction

Many millions of workers are exposed to hand-transmitted vibration from powered tools and are at risk of developing disorders in the fingers, hands, or arms.[1] [2] [3] [4]

One consequence of prolonged regular exposure to hand-transmitted vibration is impaired circulation in the fingers, often evident during or following exposure to cold. The symptoms may be first noticed as abnormally cold fingers, but disorder is often diagnosed from reports of attacks of blanching on the distal, middle, or proximal phalanges. The condition is named 'vibration-induced white finger' from the characteristic attacks of blanching that are assumed to be caused by vibration damage, although the attacks are most often provoked by cold.[4] The mechanisms involved in this heightened sensitivity to cold are not known, and so there is uncertainty as to the range of symptoms and signs that characterise the disorder.

Although it is clear that hand-transmitted vibration causes vibration-induced white finger, there is limited evidence as to the characteristics of vibration that are responsible for the injury. To obtain a number indicating the severity of an exposure to vibration (i.e. evaluate the vibration) it is necessary to make assumptions as to the importance of the vibration magnitude, the vibration frequency, the vibration direction, the daily exposure duration and life-time exposure duration. Various standards have made such assumptions so as to define uniform methods for evaluating the vibration on powered tools. Having defined a measure of vibration severity, it is possible to assess the acceptability of the vibration, in terms of the probability or severity of disorder. In International Standard 5349-1 (2001), the evaluation is performed using the root-mean-square value of the vibration acceleration after it has been frequency-weighted (using a weighting called W_h), assuming all directions of vibration to be equally important and all locations of contact with the hand to be equally likely to lead to problems.[5] The assessment of vibration severity uses the 8-hour energy-equivalent daily exposure (called $A(8)$) to predict the years of exposure before 10% of persons are likely to develop the first signs of finger blanching.

The frequency weighting inherent in current standards and directives did not evolve from epidemiological studies of the conditions causing vibration-induced white finger, or from experimental studies of the effects of different frequencies of vibration on relevant physiological responses.[6] [7] The frequency weighting was largely based on a study of how the discomfort produced by hand-transmitted vibration depends on the frequency of vibration.[8] Some recent epidemiological studies suggest that the frequency weighting may not be optimum and that, at least for the vibration on some groups of common tools, the onset of finger blanching may be predicted with greater accuracy without using frequency weighting W_h.[9] The frequency weighting has a large effect on the relative importance of vibration on different tools and, consequently, on the risks of injury and the responsibilities of employers. Improved understanding of the importance of vibration frequency therefore has considerable importance.

Contact with the vibration on a tool involves the application of force to the fingers. There are tasks that involve the application of a force without exposure to vibration that do not result in the characteristic symptoms of vibration-induced white finger, so force alone cannot explain the disorder. However, force may be expected to have some direct mechanical effect on circulation within the fingers. Furthermore, force may alter the transmission of vibration into the fingers and hand: increased force will tend to stiffen the tissues, which will change resonance frequencies and tend to increase the transmission of vibration from the area of contact with vibration.

Occupational exposures to hand-transmitted vibration result in symptoms of vibration-induced white finger after many months, usually years, of regular exposure to vibration. Laboratory studies have found reductions in blood flow during and following exposure of a finger to vibration. The effects are not restricted to the vibrated finger but are also observed in other fingers, including those on a hand not exposed to vibration. Previous experimental studies by the current authors have explored the effects of the magnitude, frequency, and duration of vibration on finger blood flow using controlled contact areas and controlled contact force.[10] [11] [12] The effects of variations in contact force on finger blood flow have not previously been investigated.

This study was designed to investigate whether the force applied by a finger affected finger blood flow and whether the effects of force interacted with the acute effects of vibration. Specifically, it was hypothesised that finger blood flow would be affected by the application of force and that the effects of vibration frequency would be dependent on the force applied to the finger.

4.2 Subjects and Methods

4.2.1 Subjects

Ten healthy male volunteers, all Caucasian, gave written informed consent to participate in the investigation. All subjects were students or office workers with no history of regular use of hand-held vibrating tools in occupational or leisure activities. Nine subjects were non-smokers. None reported cardiovascular or neurological disorders, connective tissue diseases, injuries to the upper extremities, a history of cold hands or were on medication. The mean age of the subjects was 27 (SD 2.7; range 22 - 32) years, their mean stature was 181 (SD 6.3; range 167 - 186) cm and their mean weight was 83 (SD 12.8; range 65 - 100) kg.

The length, breadth and depth of each phalanx was measured using vernier callipers and the finger volume was calculated. The mean (SD) volume of the middle right finger was 16.3 (3.0) cm^3, the little right finger was 8.1 (1.5) cm^3 and the middle left finger was 14.9 (2.2) cm^3.

4.2.2 Measures of finger circulation

Finger blood flow (FBF) was measured in the middle fingers of both hands and in the little right finger. Mercury-in-silastic strain gauges were placed around the distal phalanx at the base of the nails and plastic pressure cuffs for air inflation (9.5 x 2.5 cm) were fixed around the proximal phalanges and secured with a Velcro strip. Three pressure cuffs and strain gauges were connected to a multi-channel plethysmograph (HV*Lab*, ISVR, University of Southampton).

The FBF was measured using a venous occlusion technique: the pressure cuffs were inflated to a pressure of 60 mmHg and the increases in finger volumes were

detected by means of strain gauges according to the criteria given by Greenfield *et al.* [13] The FBF measurements were expressed in ml/100 ml/s.

Brachial systolic and diastolic blood pressures were measured in the upper right arm by an ausculatatory technique.

Room temperatures were measured using a thermocouple located adjacent to the subjects' heads.

4.2.3 EXPERIMENTAL PROCEDURE

The experiment was performed in a laboratory room with a mean (SD) temperature of 25.6 (0.4) °C. Subjects were requested to avoid caffeine consumption for two hours prior to testing and tobacco and alcohol for 12 hours prior to testing.

Each of the 10 subjects attended the laboratory on 11 occasions. In each session, they experienced five successive experimental periods of 5 minutes: (i) no force and no vibration; (ii) force and no vibration; (iii) force and vibration; (iv) force and no vibration; (v) no force and no vibration.

Throughout each session, subjects lay supine with their hands resting on platforms alongside their body at the level of the heart. After a period of acclimatisation of about 10 minutes, FBF was measured in the right and left middle fingers and the right little finger at 1-minute intervals during the 5 minutes of period (i). The right hand was then moved by the experimenter so that the intermediate phalanx of the right middle finger was positioned on a horizontal wooden platform (40 mm by 20 mm) with the intermediate phalanx across the 20 mm dimension. During period (ii) the subjects were asked to apply a downward force of either 2 or 5 N with the intermediate phalanx of their right middle finger on the platform that was mounted on an electrodynamic vibrator (VP4, Derritron). The signal from a force cell (Tedea Huntleigh) mounted between the platform and the vibrator was used to provide visual feedback on a meter for the control of downward force. The thumb, index, ring, and little fingers of the right hand were suspended in air (Figure 1). The left hand remained supported to at heart height to the left of the body.

During period (iii), sinusoidal vertical vibration was presented for 5 minutes, followed by a period with force without vibration during period (iv). The right hand was then moved by the experimenter, so that it was again supported on a platform at heart height alongside the subject for period (v).

The vibration during period (iii) was at one of two levels of 31.5 Hz (4 and 16 ms^{-2} r.m.s. unweighted) or one of two levels of 125 Hz (16 and 64 ms^{-2} r.m.s. unweighted). Using the frequency weighting in current standards, the frequency-weighted vibration magnitudes were 2.0 and 8.0 ms^{-2} r.m.s. at both 31.5 and 125 Hz. The four vibration conditions (31.5 and 125 Hz, at 2.0 and 8.0 ms^{-2} r.m.s., frequency-weighted) were combined with the two levels of force (2 N or 5 N) to give eight experimental conditions with vibration. There were, additionally, two conditions with force (2 N or 5 N) but no vibration and one condition with no force and no vibration, giving a total of 11 conditions (Table 1).

For the 5-minute duration of vibration exposure, the 8-hour energy-equivalent frequency-weighted acceleration magnitude (i.e. $A(8)$) was 0.204 ms^{-2} r.m.s. in conditions 4, 5, 8 and 9, and 0.816 ms^{-2} r.m.s. in conditions 6, 7, 10 and 11 according to International Standard 5349-1.[5]

Finger blood flow was measured at 1-minute intervals in the exposed right middle finger, the unexposed right little finger and the unexposed left middle fingers throughout the 25 minutes of each condition. The FBF measurements, expressed in absolute values (ml/100 ml/s) and as a percentage of the pre-exposure values, were averaged over the 5 minutes of each exposure period.

Brachial blood pressures were measured at the beginning and at the end of each experimental session. Room temperature was measured at 5-minute intervals.

Each of the ten subjects experienced all eleven experimental conditions on eleven separate days. Across the subject group, the eleven experimental conditions were presented in a random order. The experimental sessions lasted approximately 40 minutes. All sessions were completed within a three-week period.

The study was approved by the Human Experimental Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton (UK).

4.2.4 STATISTICAL METHODS

Data analysis was performed using the software package Stata (version 8.2 SE). The data were summarised with the mean as a measure of central tendency and the standard deviation (SD) or the standard error of mean as measures of dispersion.

The difference between paired means was tested by the Student's *t* test.

Repeated measures analysis of variance (ANOVA) was used to test the hypothesis of no difference in the vascular responses in different exposure conditions. When the compound symmetry assumption (that is, the measures have the same variance and the correlations between each pair of repeated measures are equal) was violated, a conservative test of the repeated measures factor was used by reducing the degrees of freedom of the *F* ratio (Greenhouse-Geisser method).[14] The 95% Bonferroni confidence intervals for pairwise mean comparisons of the response were used when the probability value for the *F* test of repeated measures ANOVA was $p<0.05$ (two-sided). The relation between variables with repeated measures was assessed by the generalised estimating equations (GEE) method in order to account for the within-subject correlation.[15]

4.3 Results

Figure 2 shows the overall pattern of the mean values of FBF (expressed as ml/100 ml/s and as percentages of the pre-exposure values) in the middle right (exposed, ipsilateral) finger, the little right (unexposed, ipsilateral) finger and the middle left (unexposed, contralateral) finger across the five exposure periods and the eleven exposure conditions. A repeated measures ANOVA over the whole experiment revealed significant main effects of finger, exposure period, and exposure condition. Two-way (e.g. finger $\times$ exposure condition) and three-way (finger $\times$ condition $\times$ period) interaction terms were also found to be significant ($0.05<p<0.001$). As a result, data analysis was conducted separately within each finger and across the various exposure periods and exposure conditions.

4.3.1 FINGER CIRCULATION BEFORE EXPOSURE

The vascular measurements before exposure to either push force alone or push force and vibration during period (i) (see Table 1) showed no significant changes in FBF in either the exposed or the unexposed fingers across the eleven experimental sessions (p=0.21 – 0.51). During pre-exposure, FBF averaged 1.07 to 1.34 ml/100 ml/s in the middle right finger, 1.10 – 1.39 ml/100 ml/s in the little right finger, and 1.16 – 1.46 ml/100 ml/s in the middle left finger. No differences in the pre-exposure measures of digital circulation were found between the exposed and unexposed fingers within any session.

Brachial systolic and diastolic arterial pressures measured before exposure did not change significantly within subjects across sessions (range of values across subjects and sessions: 115/70 – 130/80 mmHg). No difference was observed for the brachial arterial blood pressures measured at the beginning and the end of the eleven sessions.

In the pre-exposure period, period (i), analysis of repeated measures by the GEE method showed no significant relation between FBF and room temperature in either finger.

Neither age nor the volume of the fingers was correlated with the baseline measures of digital circulation.

Repeated measures ANOVA revealed no significant difference in the air temperature of the laboratory across the eleven experimental sessions, ranges of mean (SD) values being 25.3 (0.4) – 25.8 (0.3)°C, (p=0.52 – 0.90).

4.3.2 CIRCULATORY EFFECTS OF EXPOSURE TO PUSH FORCE

Exposure to a push force of 2 N (condition 2) and 5 N (condition 3) alone during periods (ii) to (iv) caused a significant reduction of FBF in the middle right (exposed) finger compared to the pre-exposure period (period (i)) and the recovery period

(period (v)) ($p<0.001$, Figure 2). No significant changes in the FBF of the unexposed (ipsilateral and contralateral) fingers were observed during exposure to solely push force of either 2 N or 5 N over the exposure periods from (i) to (v), ($p=0.39 – 0.64$).

Relative to blood flow without force during period (ii) in condition 1, exposure of the middle right finger to push force provoked a decrease in the FBF of the exposed finger ($p=0.025$), whereas there were no significant changes in FBF in the unexposed ipsilateral and contralateral fingers (Figure 2 and Table 2). When compared with the resting condition (condition 1), a push force of 5 N during period (ii) caused a significant reduction of FBF in the middle right finger ($p<0.01$). There was no significant difference in the change of FBF between the resting condition and a push force of 2 N during period (ii), while 5 N was associated with a greater decrease in FBF than 2 N ($p<0.05$). However, it should be noted that there was a decrease in the FBF in the middle right finger from period (i) to period (ii) in condition 1 with no force, which was persistent over the remaining exposure periods ($p<0.05$). A gradual reduction of FBF during condition 1 was also observed in the unexposed fingers from period (ii) to (v), even though repeated measures ANOVA revealed that such a decrease in blood flow was marginally not significant when compared to the pre-exposure (period (i)), ($p>0.10$).

4.3.3 Circulatory effects of combined exposure to push force and vibration

Repeated measures ANOVA revealed that combined exposure to push force and vibration during period (iii) induced significant changes in the FBF of both the exposed and the unexposed fingers (Figure 2). In the middle right (exposed) finger, a multiple comparison test (Bonferroni method) showed that a push force of 5 N combined with 125-Hz vibration at 16 or 64 ms^{-2} r.m.s. (conditions 9 and 11), a push force of 5 N combined with 31.5-Hz vibration at 16 ms^{-2} r.m.s. (condition 7), and a push force of 2 N combined with 125-Hz vibration at 64 ms^{-2} r.m.s. (condition 10) caused a significant decrease of FBF compared to the resting condition with no force and no vibration (condition 1, period (iii)), ($p=0.01$). Similar results were observed in the little right (unexposed, ipsilateral) finger ($p=0.03$), and in the middle left (unexposed, contralateral) finger ($p<0.05$), with the exception of condition 9 (5 N with 125-Hz vibration at 16 ms^{-2} r.m.s.) where the FBF was not significantly different from the resting condition.

In the middle right (exposed) finger, exposure to conditions 9 and 11 (push force of 5 N combined with 125-Hz vibration at 16 or 64 ms^{-2} r.m.s.) during period (iii) caused a more pronounced fall of FBF than condition 2 (push force of 2 N alone), condition 3 (push force of 5 N alone), condition 4 (push force of 2 N combined with 31.5-Hz vibration at 4 ms^{-2} r.m.s.), and condition 8 (push force of 2 N combined with 125-Hz vibration at 16 ms^{-2} r.m.s.), ($p<0.05$).

In the unexposed ipsilateral and contralateral fingers, exposure of the middle right finger to vibration with force in condition 10 and in conditions 7 and 11 provoked a greater reduction in FBF than exposure to a push force of 2 N and 5 N alone (conditions 2 and 3), respectively.

When the components of the exposure conditions (push force and vibration) were included separately in a repeated measures ANOVA model, some significant main effects of push force and vibration frequency during period (iii) were observed in the exposed (middle right) finger and the unexposed (little right and middle left) fingers, respectively (Table 3). Interaction terms between independent variables were not significant in either finger.

To estimate the contribution of vibration to the observed changes in FBF, the difference between the percent change in FBF (% of pre-exposure) at period (iii) and the percent change in FBF (% of pre-exposure) at period (ii) was calculated in order to remove the effect of push force. After subtracting the contribution of force to the change in FBF, the main effects of vibration frequency and vibration magnitude on the reduction of FBF were found to be highly significant in both the exposed and the unexposed fingers (Table 4).

Using the same procedure to remove the effect of force, the percentage change in FBF was regressed on the various combinations of vibration frequency and vibration magnitude used in this study (Table 5). Assuming condition 1 (no exposure to force and vibration) as the reference category, the GEE method for repeated measures analysis showed that exposure to 125-Hz vibration with an unweighted acceleration magnitude of 64 ms^{-2} r.m.s. caused a significant decrease of FBF in all (exposed and unexposed) fingers. In the little right (unexposed, ipsilateral) finger, the reduction of FBF was significantly greater during exposure to 125-Hz vibration of 64 ms^{-2} r.m.s.

than during exposure to any other combination of vibration frequency and magnitude.

A significant main effect of push force on FBF change during period (iv) (exposure to push force alone) was observed only in the middle right (exposed) finger (Table 2). Consistent with the findings during period (ii), 5 N during period (iv) induced a greater decrease in the FBF of the exposed finger than either no force or 2 N force ($p<0.05$). No significant effect of push force was observed in the unexposed ipsilateral and contralateral fingers during exposure period (iv).

Finally, there were no significant changes in FBF in either the exposed or the unexposed fingers during exposure period (v) (i.e. recovery) across the eleven experimental sessions ($p=0.15 – 0.48$).

4.4 Discussion

The decrease in FBF in the middle right finger from period (i) to period (ii) in condition 1 with no force suggests that some factors other than force and vibration had an influence of finger blood flow. In all five periods of each condition, the hand was at the level of the heart, but it was moved laterally by the experimenter at the end of the first five minutes, and before the last five minutes. In conditions 2 to 11 the subject then applied a downward force with the middle phalanx of the middle finger, whereas in condition 1 the hand was in the same posture with the finger resting on the contactor without applying any force. The change in finger blood flow between periods (i) and (ii) in condition 1 may have been associated with a change in the height of the finger relative to the heart (by about 10 cm) during the lateral movement needed to place the finger on the wooden platform, or slight compression on the digital arteries when the middle right finger rested on the wooden platform.

In this study, there was a gradual fall in the resting blood flow in the exposed and unexposed fingers over the exposure periods in condition 1. A downward trend in FBF in resting conditions has been observed in other experimental studies and was attributed to both prolonged immobility of the subjects and the prolonged inactivity in their fingers.[16]

4.4.1 Effects of push force

In this study, increasing push forces were associated with increasing reductions of FBF in the exposed finger, while no change in FBF was observed in the unexposed ipsilateral and contralateral fingers. Such a reduction of FBF in the exposed finger is likely due to local mechanical compression of the digital arteries by the applied force. This finding is consistent with those reported in other laboratory investigations which showed a decrease in either finger skin temperature or blood flow when the experimental subjects exerted constant push and/or grip forces on either wooden cylinders or metal handles, suggesting that the forces required to operate vibratory tools can have adverse acute effects on finger circulation.[17] [18] [19] [20]

4.4.2 Effects of vibration

After eliminating the effects of force, there was evidence in all fingers (exposed and not exposed to vibration) and at both frequencies (31.5 and 125 Hz) of a greater reduction in FBF with the greater magnitude of vibration. This is consistent with our previous studies.[11] [12] That the effect of vibration magnitude is present on unexposed fingers indicates that, unlike the effects of force, the mechanisms responsible for vasoconstriction during exposure to hand-transmitted vibration are not solely local.

After eliminating the effects of force, there was evidence in all fingers (exposed and not exposed to vibration) and at both magnitudes (low and high) of a greater reduction in FBF with the higher frequency of vibration. The low vibration magnitudes (4 ms^{-2} r.m.s. at 31.5 Hz and 16 ms^{-2} r.m.s. at 125 Hz) had the same frequency-weighted acceleration magnitude (2.0 ms^{-2} r.m.s.) according to current standards and the high vibration magnitudes (16 ms^{-2} r.m.s. at 31.5 Hz and 64 ms^{-2} r.m.s. at 125 Hz) also had the same frequency-weighted acceleration magnitude (8.0 ms^{-2} r.m.s.). The high vibration magnitude at 31.5 Hz and the low vibration magnitude at 125 Hz were the same (i.e. 16 ms^{-2} r.m.s.), and it may be seen in Table 5 that these conditions resulted in similar reductions in FBF relative to the corresponding conditions without vibration. The finding that the same unweighted acceleration gives broadly similar vasoconstriction whereas the same frequency-weighted acceleration

does not, is consistent with our previous studies of acute changes in FBF caused by hand-transmitted vibration.[12] It is also consistent with some epidemiological studies of the development of finger blanching in users of vibratory tools.[9]

4.4.3 Influence of push force on the effects of vibration

If the application of force caused a change in the dynamic response of the finger or hand, it would be expected to alter the sensitivity of the finger to changes in FBF at one or both vibration frequencies.

By various means, force applied at the finger could alter the changes in FBF similarly at both frequencies, for example by increasing the transmission of vibration by a similar amount to adjacent tissues. If so, the reductions in FBF with the greater force (5 N) would be expected to differ from those with the lower force (2 N). In the middle right (exposed) finger, exposure to conditions 9 and 11 (push force of 5 N combined with 125-Hz vibration at 16 or 64 ms^{-2} r.m.s.) during period (iii) caused a more pronounced fall of FBF than condition 2 (push force of 2 N alone), condition 3 (push force of 5 N alone), condition 4 (push force of 2 N combined with 31.5-Hz vibration at 4 ms^{-2} r.m.s.), and condition 8 (push force of 2 N combined with 125-Hz vibration at 16 ms^{-2} r.m.s.), ($p<0.05$), consistent with a force of 5 N with vibration producing a greater decrease in FBF than either 2 N or 5 N alone, and greater than with 2N combined with vibration.

4.4.4 Comparison of results with our previous studies

In respect of the effects of vibration magnitude and vibration frequency, the results are consistent with our previous findings: greater reduction in FBF with greater magnitudes and greater reductions with higher frequencies when vibrations of equal frequency-weighted vibration are compared.[11] [12] However, the effects of force appear somewhat different from our previous research.

In previous studies [10] [12], no difference has found between finger blood flow measured with and without force, but the contact conditions were not identical to those used here. Bovenzi *et al.* [10] [12] applied a 10 N downward force on a flat wooden plate with the right hand such that the pressure was exerted over the phalanges of several fingers, and found no effect of force on FBF. In this study,

lower forces (2 and 5 N) resulted in clear reductions in FBF but the force was exerted solely by the middle phalanx of the middle finger. An obvious possible explanation is that the increased pressure at this location that may have compressed the vasculature sufficiently to impair circulation.

4.4.5 Consequences for vibration evaluation and assessment

Since the pressure applied to the finger in this study resulted in reduced finger blood flow without vibration, it is reasonable to wonder to what extent the pressures associated with the grips applied to the handles of tools also reduce finger blood flow. It is often assumed that a minimisation of grip force is desirable because it may reduce the transmission of vibration to the hand. Since grip can reduce finger blood flow, this is an additional reason for recommending the minimisation of grip forces and, further, the investigation of grip designs to minimise the reduction in finger blood flow.

Contact between the hand and vibratory hand tools is not limited to the fingers but extends into the palm of the hand. Further study of the effects of force, pressure and contract location in the palm of the hand is desirable so as to identify means of holding tools with minimum effects of finger blood flow.

4.5 Conclusions

Forces as low as 2 N and 5 N applied to a finger can greatly reduce blood flow in the finger to which force is applied. The acute vascular effects of vibration cause reductions in finger blood flow that are additional to the reductions caused by force and are not limited to the finger experiencing force and vibration. In all fingers (both those exposed and those not exposed to vibration), the greater the magnitude of vibration, the greater the reduction in finger blood flow. In all fingers (exposed and not exposed to vibration), when the vibration was frequency-weighted according to current standards, vibration at 125 Hz caused a greater reduction in finger blood flow than vibration at 31.5 Hz.

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Table 1. Experimental design of the study: condition of exposures to push force alone (newtons) and combinations of push force and vibration with two frequencies (Hz) and three acceleration magnitudes (ms^{-2} r.m.s.) having two identical frequency-weighted acceleration magnitudes according to the International Standard 5349-1 (2.0 and 8.0 ms^{-2} r.m.s., see methods). Condition 1 is a control condition.

Condition	Exposure period (time interval)						
	(i) (1-5 min)	(ii) (6-10 min)	(iii) (11-15 min)			(iv) (16-20 min)	(v) (21-25 min)
	Force (N)	Force (N)	Force (N)	Vibration (Hz)	Vibration (ms^{-2})	Force (N)	Force (N)
1	0	0	0	0	0	0	0
2	0	2	2	0	0	2	0
3	0	5	5	0	0	5	0
4	0	2	2	31.5	4	2	0
5	0	5	5	31.5	4	5	0
6	0	2	2	31.5	16	2	0
7	0	5	5	31.5	16	5	0
8	0	2	2	125	16	2	0
9	0	5	5	125	16	5	0
10	0	2	2	125	64	2	0
11	0	5	5	125	64	5	0

Table 2. Repeated measures analysis of variance for testing the effects of push force on the percentage change in finger blood flow (% of pre-exposure) at exposure periods (ii) and (iv), (see Table 1). Mean square (MS) values, *F*-statistic and probability levels for the effect of push force are shown.

Exposure period	Middle right finger (exposed, ipsilateral)			Little right finger (unexposed, ipsilateral)			Middle left finger (unexposed, contralateral)		
	MS	*F*	p-value	MS	*F*	p-value	MS	*F*	p-value
Period (ii)	1414	3.85	0.025	12	0.02	0.982	79	0.24	0.789
Period (iv)	5002	8.25	0.001	947	1.10	0.337	1062	2.27	0.109

Table 3. Repeated measures analysis of variance for testing the effects of push force, vibration frequency and vibration magnitude on the percentage change in finger blood flow (% of pre-exposure) at exposure period (iii), (see Table 1). Mean square (MS) values, *F*-statistic and probability levels for the main effects of push force, vibration frequency and vibration magnitude and for the interaction terms are shown.

Source of variation	Middle right finger (exposed, ipsilateral)			Little right finger (unexposed, ipsilateral)			Middle left finger (unexposed, contralateral)		
	MS	*F*	p-value	MS	*F*	p-value	MS	*F*	p-value
Force	1236	3.34	0.039	44	0.05	0.245	47	0.11	0.899
Vibration frequency	947	2.56	0.083	6556	7.61	0.001	2341	5.34	0.006
Vibration magnitude	533	1.44	0.233	1887	2.19	0.142	1217	2.78	0.099
Force × vibration frequency	268	0.72	0.488	690	0.80	0.452	217	0.50	0.610
Force × vibration magnitude	819	2.22	0.140	17	0.02	0.889	23	0.05	0.819
Vibration frequency × vibration magnitude	17	0.05	0.831	967	1.12	0.292	515	1.18	0.281

Table 4. Repeated measures analysis of variance for testing the effects of push force, vibration frequency and vibration magnitude on the percentage change in finger blood flow (% of pre-exposure). The change in finger blood flow (FBF) was calculated as the difference between the percent change in FBF (% of pre-exposure) at exposure period (iii) and the percent change in FBF (% of pre-exposure) at exposure period (ii), (see Table 1). Mean square (MS) values, *F*-statistic and probability levels for the main effects of push force, vibration frequency and vibration magnitude and for the interaction terms are shown.

Source of variation	Middle right finger (exposed, ipsilateral)			Little right finger (unexposed, ipsilateral)			Middle left finger (unexposed, contralateral)		
	MS	*F*	p-value	MS	*F*	p-value	MS	*F*	p-value
Force	4	0.01	0.987	3	0.01	0.993	129	0.32	0.724
Vibration frequency	2531	9.03	0.001	8698	19.7	0.001	3494	8.72	0.001
Vibration magnitude	1632	5.82	0.018	6820	15.5	0.001	2310	5.77	0.018
Force × vibration frequency	112	0.40	0.671	392	0.89	0.415	462	1.15	0.320
Force × vibration magnitude	137	0.49	0.486	1109	2.51	0.116	234	0.58	0.447
Vibration frequency × vibration magnitude	74	0.26	0.609	1319	2.99	0.087	67	0.17	0.684

Table 5. Regression of percentage change in finger blood flow (% of pre-exposure) on exposure to push force and vibration. The change in FBF was calculated as the difference between the percent change in FBF (% of pre-exposure) at exposure period (iii) and the percent change in FBF (% of pre-exposure) at exposure period (ii), (see Table 1). Regression coefficients (robust standard errors) are estimated by the generalised estimating equations method for repeated measures data, assuming no exposure to push force and no exposure to vibration as the reference category. P-values are adjusted for multiple comparisons (Bonferroni method).

Predictors	Change in finger blood flow (%)		
	Middle right finger (exposed, ipsilateral)	Little right finger (unexposed, ipsilateral)	Middle left finger (unexposed, contralateral)
Constant (no exposure)	1.7 (6.2)	4.4 (4.5)	4.0 (6.9)
Force 2 N	0.1 (7.9)	0.9 (6.5)	- 0.9 (7.5)
Force 5 N	0.0 (8.9)	0.4 (5.2)	0.7 (7.7)
Vibration 31.5 Hz, 4 ms^{-2} r.m.s.	- 6.1 (6.2)	- 2.3 (7.1)	- 6.1 (5.5)
Vibration 31.5 Hz, 16 ms^{-2} r.m.s.	- 13.2 (6.1)	- 12.6 (6.0)	- 15.0 (5.9)
Vibration 125 Hz, 16 ms^{-2} r.m.s.	- 11.0 (5.1)	- 14.1 (6.3)	- 13.0 (6.4)
Vibration 125 Hz, 64 ms^{-2} r.m.s.	- 22.0 (5.4)	- 40.6 (6.0)	- 25.5 (5.3)

Middle right finger: (vibration 125 Hz, 64 ms^{-2}) *vs* (no exposure): p<0.001.

Little right finger: (vibration 125 Hz, 64 ms^{-2}) *vs* (no exposure): p<0.001;
(vibration 125 Hz, 64 ms^{-2}) *vs* (force 2 N): p<0.001;
(vibration 125 Hz, 64 ms^{-2}) *vs* (force 5 N): p<0.001;
(vibration 125 Hz, 64 ms^{-2}) *vs* (vibration 31.5 Hz, 4 ms^{-2}): p<0.001;
(vibration 125 Hz, 64 ms^{-2}) *vs* (vibration 31.5 Hz, 16 ms^{-2}): p=0.02;
(vibration 125 Hz, 64 ms^{-2}) *vs* (vibration 125 Hz, 16 ms^{-2}): p=0.013.

Middle left finger: (vibration 125 Hz, 64 ms^{-2}) *vs* (no exposure): p<0.001.

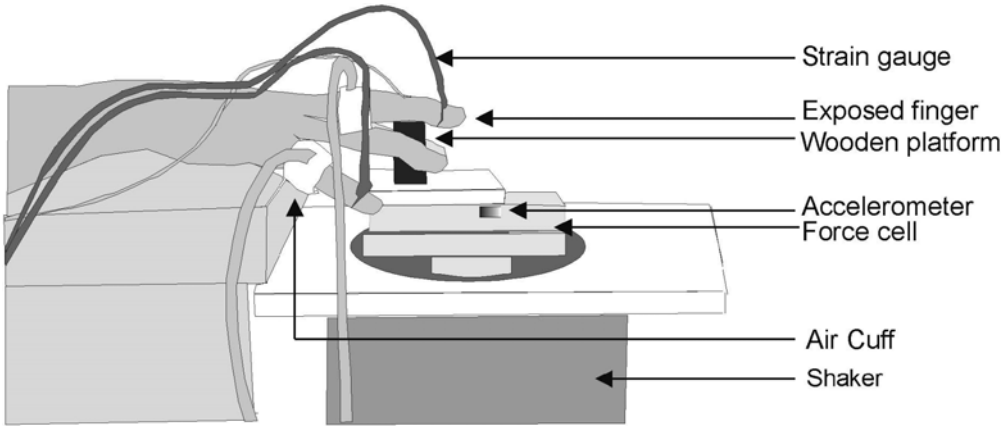

Figure 1. Experimental set up for generating the vibration, controlling the contact force, and measuring finger blood flow.

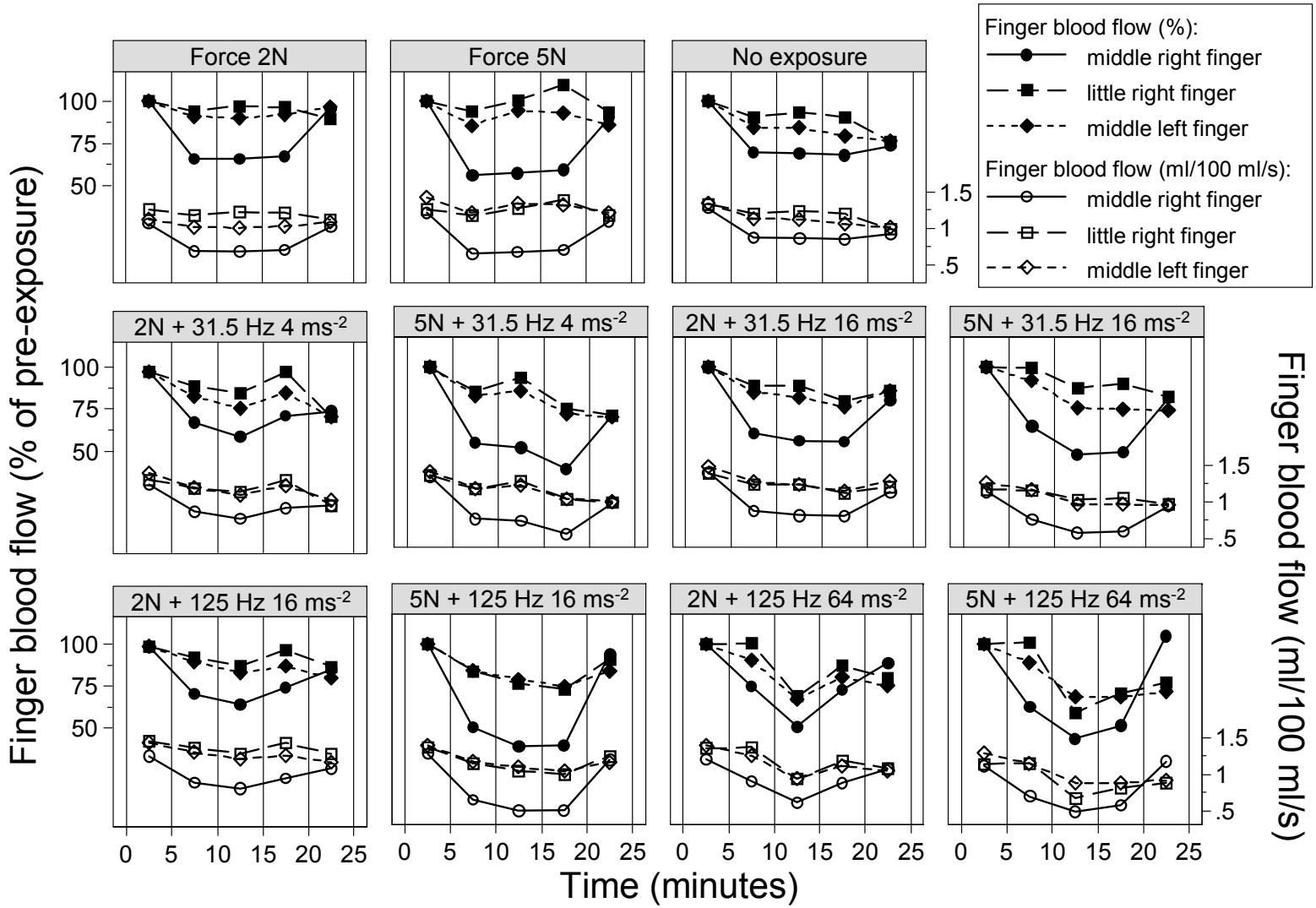

Figure 2. Finger blood flow (FBF, ml/100 ml/s) and percentage change of FBF (% of pre-exposure) in the middle right finger (exposed, ipsilateral to push force and vibration), the little right finger (unexposed, ipsilateral), and the middle left finger (unexposed, contralateral) during the various exposure conditions (see Table 1). Plotted symbols are mean values. Repeated measures ANOVA: