Published as: European Journal of Applied Physiology, 114, (8), 1591-1603.
Published version available from M.J.Griffin@soton.ac.uk

Total number of pages: 19

Total number of tables: 1

Total number of figures: 4

Total number of references: 31

Relation between vibrotactile perception thresholds and reductions in finger blood flow induced by vibration of the hand at frequencies in the range 8 to 250 Hz

Ying Ye and Michael J Griffin

Human Factors Research Unit, Institute of Sound and Vibration Research, University of Southampton, Southampton SO17 1BJ, England

Correspondence address:
Professor Michael J Griffin
Human Factors Research Unit
Institute of Sound and Vibration Research
University of Southampton
Southampton SO17 1BJ
England

Telephone: (+44) 023 8059 2277
Facsimile: (+44) 023 8059 2927

E-mail: M.J.Griffin@soton.ac.uk

Abstract

Purpose This study investigated how the vasoconstriction induced by vibration depends on the frequency of vibration when the vibration magnitude is defined by individual thresholds for perceiving vibration (i.e., sensation levels, SL).

Methods Fourteen healthy subjects attended the laboratory on seven occasions: for six vibration frequencies (8, 16, 31.5, 63, 125, or 250 Hz) and a static control condition. Finger blood flow (FBF) was measured in the middle fingers of both hands at 30-second intervals during five successive periods: (i) no force or vibration, (ii) 2-N force, no vibration, (iii) 2-N force, vibration, (iv) 2-N force, no vibration, (v) no force or vibration. During period (iii), vibration was applied to the right thenar eminence via a 6-mm diameter probe during 10 successive 3-minute periods as the vibration magnitude increased in 10 steps (-10 dB to +40 dB SL).

Results With vibration at 63, 125, and 250 Hz, there was vasoconstriction on both hands when the vibration magnitude reached 10 dB SL. With vibration at 8, 16, and 31.5 Hz, there was no significant vasoconstriction until the vibration reached 25 dB SL. At all frequencies, there was greater vasoconstriction with greater magnitudes of vibration.

Conclusions It is concluded that at the higher frequencies (63, 125, and 250 Hz) the Pacinian channel mediates vibrotactile sensations near threshold and vasoconstriction occurs when vibration is perceptible. At lower frequencies (8, 16, and 31.5 Hz), the Pacinian channel does not mediate sensations near threshold and vasoconstriction commences at greater magnitudes when the Pacinian channel is activated.

Keywords Vibration-induced white finger · Finger blood flow · Hand-arm vibration syndrome · Hand-transmitted vibration · Vibrotactile perception thresholds

Abbreviations

%FBF	percentage change in finger blood flow
BMI	body mass index
dB	decibel
FAI	fast adapting I
FAII	fast adapting II
FBF	finger blood flow
FST	finger skin temperature
IQR	inter-quartile range
NPI	non-Pacinian I
NPII	non-Pacinian II
NPIII	non-Pacinian III
P	Pacinian

Published as: European Journal of Applied Physiology, 114, (8), 1591-1603.
Published version available from M.J.Griffin@soton.ac.uk

SD	standard deviation
SL	sensation level
VPM	vibrotactile perception meter
VWF	vibration-induced white finger

Published as: European Journal of Applied Physiology, 114, (8), 1591-1603.
Published version available from M.J.Griffin@soton.ac.uk

Introduction

Occupational exposures to hand-transmitted vibration from powered tools can result in vascular disorder in the fingers, commonly called vibration-induced white finger (VWF). The condition may be visible during attacks of finger blanching provoked by cold, and diagnosed by excessive cold-induced reductions in finger blood flow or finger systolic blood pressure (Griffin and Bovenzi, 2002). Vibration-induced white finger affects the control of peripheral circulation in the fingers (Olsen *et al.*, 1987), although other changes are also reported in severe cases (e.g., Takeuchi *et al*., 1986).

The symptoms of vibration-induced white finger mostly arise after many years of regular exposure to hand-transmitted vibration and may be considered a chronic effect. There are also acute effects of hand-transmitted vibration in which finger blood flow is reduced during and immediately after exposure to vibration, with reductions occurring on the hand exposed to vibration and on the contralateral hand not exposed to vibration (Bovenzi *et al.,* 1998, 1999, 2000). It is not yet understood why vibration affects digital circulation or which mechanisms are involved in the dis-regulation of circulation. A common explanation has been that a central sympathetic reflex to vibration alters finger blood flow (Gemne, 1994; Bovenzi *et al.*, 2006). For such a reflex to be involved there must be mediation of the vibratory stimulus, such as the excitation of mechanoreceptors by vibration (Ye and Griffin, 2011a).

Thresholds for perceiving vibration of the hand are determined by one or more of four psychophysical channels associated with mechanoreceptors in the glabrous skin of the hand (Bolanowski *et al.*, 1988). The most sensitive channel depends on the frequency of the vibration, the contact conditions, the location on the hand, and some other factors. The Pacinian (P) channel, mediated by Pacinian corpuscles (also called FA II units), has the lowest threshold at frequencies greater than about 40 Hz when using a 6-mm vibrating contactor (Morioka and Griffin, 2005; Morioka, *et al*., 2008), and exhibits both spatial and temporal summation: reduced thresholds with increased area of excitation and increased duration of vibration (Verrillo 1962, 1963). Of the three non-Pacinian channels, the NPI channel often determines thresholds at frequencies between 4 and 40 Hz and is associated with Meissner corpuscles (FA I units), whereas the NPII and NPIII channels are associated with slow adapting fibres and have been identified from the results of psychophysical experiments (Capraro *et al.*, 1979, Bolanowski *et al.*, 1988, Verrillo *et al.*, 2002). The NPII channel, which is excited by vibration in the same frequency range as the Pacinian channel, is sensitive to the stretching of the skin and in most conditions has a higher threshold than the Pacinian channel (Bolanowski *et al.*, 1988). The NPIII channel may have a lower threshold than other channels in the range 0.4 to 4 Hz (Greenspan and Bolanowski, 1996). According to the frequency and the magnitude of vibration and the contact conditions, different channels are activated by vibration.

Current standards for evaluating the severity of occupational exposures to hand-transmitted vibration assume that sensitivity to vibration acceleration is independent of the frequency of vibration at frequencies from 8 to 16 Hz but reduces in inverse proportion to the frequency of vibration from 16 to 1000 Hz. This assumption underlies frequency weighting W_h, used to predict the severity of hand-transmitted vibration (ISO 5349-1, 2001). Laboratory studies of acute responses to hand-transmitted vibration have found that with the same frequency-weighted acceleration at all frequencies there is more vasoconstriction in the fingers (on both the exposed hand and the unexposed hand) with frequencies greater than 30 Hz than with lower frequencies (Furuta *et al.*, 1991; Bovenzi *et al.*, 2000; Thompson and Griffin, 2009). With vibration having the same velocity at frequencies from 16 to 250 Hz (a frequency-weighted acceleration of 5.5 ms^{-2} r.m.s.), Bovenzi *et al*. (2000) found that finger blood flow in the exposed hand was strongly reduced over the range 31.5 to 250 Hz, but only slightly reduced with the 16-Hz vibration. The experimental studies with acute exposures to vibration therefore suggest the acute vascular response is not well predicted using the frequency weighting employed in current standards. The frequency weighting was based on understanding of the frequency-dependence of the discomfort caused by hand-transmitted vibration, not studies of acute vascular responses or acute neurological responses to vibration or epidemiological studies of chronic responses to occupational exposures to hand-transmitted vibration.

With greater magnitudes of vibration there is greater vasoconstriction in the digital vessels (Bovenzi *et al.*, 1999; Thompson and Griffin, 2009; Ye and Griffin, 2011a). With progressive increases in the frequency-weighted acceleration from 0 to 15 ms^{-2} r.m.s., vibration induces progressively greater reductions in finger blood flow at all frequencies in the range 16 to 315 Hz (Thompson and Griffin, 2009). Reductions in the blood flow in individual fingers induced by 125-Hz vibration at 0.5 and 1.5 ms^{-2} r.m.s. have been found to be associated with individual absolute thresholds for perceiving 125-Hz vibration via the Pacinian channel (Ye and Griffin, 2011a). This suggests some vascular changes provoked by vibration may be related to the sensations produced by the vibration, as assumed for frequency weighting W_{h}, at least for vibration conditions where sensations are mediated by the Pacinian channel.

Large inter-subject variability has been observed in the vasoconstriction caused by vibration, with reductions in finger blood flow differing by as much as 50% (Ye and Griffin, 2011b). This may be partly explained by the correlation between perception thresholds mediated by the Pacinian channel and the vibration-induced vasoconstriction: finger blood flow is less affected by vibration in subjects with higher thresholds at 125-Hz (Ye and Griffin, 2011a, 2013).

In the light of previous findings, the magnitude of vibration presented to each subject in the present study was expressed relative to the subject's absolute threshold for perceiving the vibration in the same conditions (i.e., expressed as a sensation level, SL). The study investigated the relation between the magnitude of vibration and reductions in finger blood flow induced by vibration over the frequency range 8 to 250 Hz. With vibration applied to the thenar eminence of the right hand, it was expected that the Pacinian channel would have the lowest threshold at the higher frequencies (i.e., 63, 125, and 250 Hz) and would therefore determine the vibrotactile threshold. It was hypothesized that there would be vasoconstriction in digits on both hands when the vibration magnitude exceeded thresholds at these frequencies. At the lower frequencies (i.e., 8, 16, and 31.5 Hz), it was expected that non-Pacinian channels would mediate sensations at threshold, and that the Pacinian channel would not be activated until the vibration was greater than the threshold for perception. It was therefore hypothesized that reductions in finger blood flow at the lower frequencies would not be related to thresholds for perceiving vibration at these frequencies.

Methods

Apparatus

Vibrotactile perception thresholds were measured at six frequencies (8, 16, 31.5, 63, 125 and 250 Hz) using an *HVLab* Vibrotactile Perception Meter (VPM, University of Southampton) and the von Békésy algorithm. The vibration intensity increased (at 3 dB/s) until the subject perceived vibration and pressed a hand-held button; the vibration intensity subsequently decreased (at 3 dB/s) until the subject no longer felt the vibration and released the button. The minimum duration of each measurement was 30 seconds and the minimum number of reversals (i.e., button presses and button releases) was six. If necessary, the measurements continued beyond 30 seconds until six reversals were obtained. Thresholds were calculated as the arithmetic mean of the mean peak and the mean trough (expressed in ms^{-2} r.m.s.), the first cycle of the measurement being ignored.

Finger blood flow (FBF) in the middle finger of both hands was measured with a venous occlusion method using an *HVLab* multi-channel plethysmograph (University of Southampton. On both fingers, a strain gauge was placed at the base of the finger nail and a pressure cuff for air inflation was fixed around the proximal phalanx. The pressure cuffs were inflated to a pressure of 60 mm Hg (8.0 kPa), and the rises in fingertip volumes were detected by means of the strain gauges according to the criteria given by Greenfield *et al.* (1963). The FBF measurements were expressed as millilitres per 100 millilitres per second (ml/100ml/s).

Finger skin temperature (FST) was measured using k-type thermocouples attached by micro pore tape to the distal phalanges of the right and left middle fingers, with the adhesive tape restricted to the palmar side so as not to cause occlusion of blood vessels. The room temperature was measured by a mercury-in-glass thermometer to an accuracy of ± 0.5ºC. The thermometer was located close to the heads of the subjects.

Vertical sinusoidal vibration at 8, 16, 31.5, 63, 125, and 250 Hz was generated by the VPM controlled via a computer using *HVLab* Data Acquisition and Analysis Software (*HVLab* version 3.81). Visual feedback for the control of the downward force was supplied to the subject by the control unit of the VPM.

Subjects

Fourteen male volunteers participated in the study. They were all university students aged between 18 to 30 years (mean 22.7 years, standard deviation 3.0), healthy (no indication of cardiovascular or neurological disorders, connective-tissue diseases, injuries to the upper extremities, or a history of cold hand), non-smokers, right handed, and had no history of regular use of hand-held vibratory tools in occupational or leisure activities. The mean stature of subjects was 176.4 (SD: 4.4, range: 165-188) cm, their mean weight was 74.1 (SD: 7.8, range: 52-89) kg, and their mean body mass index (BMI) was 23.7 (SD: 2.6, range: 18.5-26.4) $kg.m^{-2}$. The finger length and the width and depth of each phalanx of the right and left middle fingers were measured with vernier callipers to an accuracy of 0.5 mm, and the volumes of these fingers calculated. The mean finger volumes were 19.0 (SD: 5.1) cm^3 and 19.1 (SD: 5.0) cm^3 for the middle fingers of the right and left hands, respectively. The subjects were requested to avoid consuming caffeine for 2 hours and alcohol for 12 hours prior to the testing. They were also asked not take any high intensity exercise for 12 hours prior to testing. A health questionnaire required the reporting of all current medications. The experiment was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research. Informed consent to participate in the experiment was given by all subjects.

Experimental sessions

Each subject attended on seven separate days on which they experienced seven conditions, consisting of six different vibration frequencies (8, 16, 31.5, 63, 125, or 250 Hz) and one control condition with no vibration. The order of presentation of conditions was randomized. Vibrotactile perception thresholds at the appropriate vibration frequency were measured at the beginning of each session.

In each of the six sessions with vibration, finger blood flow was measured in the left and right middle fingers at 30-second intervals throughout five successive experimental periods, with no break between the five periods: (i) pre-exposure (5 minutes): no force and no vibration; (ii) pre-exposure application with force (5 minutes): 2-N force and no vibration; (iii) vibration (30 minutes): 2-N force and vibration at either 8, 16, 31.5, 63, 125 or 250 Hz with vibration magnitudes at 10 sensation levels (-10 dB, -5 dB, 0 dB, 5 dB, 10 dB, 15 dB, 20 dB, 25 dB, 30 dB and 40 dB), with 3 minutes at each sensation level; (iv) post-exposure with force (5 minutes): 2-N force and no vibration; (v) recovery (5 minutes): no force and no vibration (Figure 1). In the control condition there was 2-N force during period (iii) for 30 minutes with no vibration.

Figure 1 ABOUT HERE

Procedure

The experiment was performed in a laboratory with a mean air temperature of 25.5 ºC (SD 0.5 ºC). The finger skin temperature was measured and the experiment proceeded only if the skin temperature was greater than 30°C.

Initially, subjects sat on a seat next to a table supporting the vibrotactile perception meter. The height of the seat was adjusted so that subjects were comfortable and able to maintain a force between their hands and the surround on the VPM applicator. Subjects applied a downward force of 2 N with their thenar eminence on a rigid flat circular surround having a circular hole (10-mm diameter) within which a flat circular probe (6-mm diameter) flush with the surround (and separated by a 2-mm gap) vibrated at the required frequency.

The vascular response to vibration was determined using vibration applied by the *HVLab* VPM.The absolute magnitudes of the vibration stimuli presented to the subjects at each frequency were determined by the individual vibrotactile perception thresholds at that frequency. The vibration was presented at 10 magnitudes, increasing in 5 dB steps from -10 dB SL to 30 dB SL and then to 40 dB SL, where a sensation level, SL, of 0 dB corresponds to the individual's threshold for perceiving that frequency of vibration with the same contact conditions.

Subjects wore light clothing and lay supine throughout the measurement of finger blood flow, with both arms and both hands supported at heart level. After a period of acclimatisation around 20 minutes, finger blood flow and finger skin temperature were measured simultaneously in the left and right hand. For the first 5 minutes in measurement period (i), the base-line values of FBF were obtained and then, with the help of the experimenter, the subjects were asked to apply a downward force of 2 N with the thenar eminence of their right hand on the applicator of the VPM during period (ii). The hand was in a comfortable posture with all fingers suspended without contact. Visual feedback for the control of the downward force was supplied by the control unit of the VPM. After period (iv), the right hand was gently moved by the experimenter and supported at heart height alongside the subject for another 5 minutes during period (v). The left hand was supported at heart level and kept motionless with no force and no vibration throughout all five periods.

Analysis methods

Vibration magnitudes are expressed as sensation levels in dB, so as to show the magnitudes relative to the vibrotactile perception threshold:

$$\text{Sensation level, SL (dB)} = 10 \log_{10} (a_{\text{rms}} / a_{\text{Th}})$$

where a_{rms} is the acceleration magnitude and a_{Th} is the perception threshold, both in ms^{-2} r.m.s. (unweighted).

Finger blood flow was expressed as a percentage of the pre-exposure finger blood flow measured in period (i) (i.e., %FBF).

Published as: European Journal of Applied Physiology, 114, (8), 1591-1603.
Published version available from M.J.Griffin@soton.ac.uk

Data analysis was performed using the software package SPSS (version 17.0). The data were summarised with the median as a measure of central tendency and the inter-quartile range as a measure of dispersion. Non-parametric tests (Friedman test for *k*-related samples, Wilcoxon matched-pairs signed ranks test for two-related samples, and Spearman test for correlation coefficient) were employed in the statistical analysis.

The Friedman test was used to test for differences within the 10 finger blood flow measurements during the 5-minute pre-exposure period, the 5-minute pre-exposure application of force, the 5-minute post-exposure application of force, the 5-minute recovery period, and the 60 finger blood flow measurements during the 30-minute vibration period. A Wilcoxon matched-pairs signed ranks test was then used to investigate differences between the median finger blood flow during the five periods and differences between each pair of the seven exposure conditions. A Spearman test was used to investigate the relation between the subjects' individual perception thresholds, finger skin temperatures, and finger blood flows.

The criterion for statistical significance was $p<0.05$.

Results

Vibration thresholds

The median and inter-quartile range of the vibration perception threshold at each of the six frequencies, and the consequent ranges of vibration magnitudes used when measuring finger blood flow, are listed in Table ~~2~~1.

TABLE ~~2~~ 1 ABOUT HERE

Thresholds at any two frequencies would be expected to be more highly correlated when the same channel mediates the two thresholds. Thresholds at 8, 16, 31.5 and 63 Hz were correlated ($p<0.05$), except for thresholds at 8 and 63 Hz ($p=0.133$) and thresholds at 16 and 63 Hz ($p=0.089$). Thresholds at 63, 125, and 250 Hz were also correlated with each other ($p<0.05$).

There were no correlations between thresholds at the thenar eminence and skin temperature (measured during period (i)) ($p>0.1$).

Room temperature and finger skin temperature

The temperature in the laboratory did not vary during the 50-minute duration of the experiment in any of the seven experimental conditions ($p>0.1$). The median room temperature did not differ between the seven conditions ($p>0.1$).

The median finger skin temperatures on the right middle finger and the left middle finger during period (i) (pre-exposure without force), period (ii) (pre-exposure with force), period (iii) (exposure to 8 to 250-Hz vibration at sensation levels from -10 dB to 40 dB, or no vibration), period (iv) (post-exposure with force), and period (v) (post-exposure without force) are shown in Figure 2.

FIGURE 2 ABOUT HERE

In the control condition without vibration, the finger skin temperature on the distal phalanx of the right middle finger did not change during the 50-minute duration of the experiment (p=0.46). However, during each of the six conditions with vibration there were progressive reductions in skin temperature as the vibration magnitude increased (p<0.05). Similarly, on the distal phalanx of the left middle finger there was no change in temperature during the control condition (p=0.27) but a reduction in temperature during vibration (p<0.05), except with 8-Hz vibration (p=0.69). In each of the six vibration conditions, there was a significant reduction in the median temperature on the right hand relative to the control condition during period (iii) (vibration exposure, p<0.05), period (iv) (post-exposure application of force, p<0.05) and period (v) (recovery, p<0.05), but not during period (i) (pre-exposure, p>0.1), or period (ii) (pre-exposure application of force, p>0.1). There were similar changes on the left hand, with reductions in temperature relative to the control condition during period (iii) (p<0.05), period (iv) (p<0.05), and period (v) (p<0.05) when exposed to vibration at 16, 31.5, 63, 125, and 250 Hz. The median finger skin temperature reduced with increasing frequency of vibration from 8 to 250 Hz on both the exposed right hand and the unexposed left hand during period (iii), period (iv), and period (v) (p<0.05), except between 125 and 250 Hz on both hands and between 31.5 and 63 Hz on the unexposed left hand.

Finger blood flow

For each subject, the percentage change in finger blood flow (%FBF) was calculated relative to the median of the 10 measures of FBF during the 5-minute pre-exposure period.

The median %FBF in the right middle finger during period (i) (pre-exposure without force), period (ii) (pre-exposure with force), period (iii) (exposure to vibration at sensation levels from -10 dB to 40 dB, or no vibration), period (iv) (post-exposure with force), and period (v) (post-exposure without force) is shown in Figure 3.

Figure 3 ABOUT HERE

Finger blood flow during period (i): pre-exposure period

There was no significant change in FBF on the exposed right hand or the unexposed left hand over the 10 measurements during the 5-minute pre-exposure period in any condition (i.e., with the six vibration conditions or in the control condition, p>0.1). The median individual FBF over the 10 measurements did not differ between the seven conditions on either hand (p>0.1). There was no significant difference in FBF between the exposed hand and the unexposed hand in any of the seven conditions (p>0.1).

Finger blood flow during period (ii): pre-exposure application of force

There were no significant changes in %FBF on the exposed right hand or the unexposed left hand over the 10 measurements during the pre-exposure application of force for any of the

Published as: European Journal of Applied Physiology, 114, (8), 1591-1603.
Published version available from M.J.Griffin@soton.ac.uk

seven conditions (p>0.1), and the median %FBF did not differ across the seven conditions on either hand (p>0.1). There was no significant difference in the median %FBF during period (ii) (pre-exposure application of force) compared to period (i) (the pre-exposure period) (p>0.1 for all seven conditions) on either the exposed right hand or the unexposed left hand, except for the exposed right hand in the 125-Hz vibration condition (p=0.037). It may be concluded that the 2-N force applied by the right hand did not change finger blood flow on either hand.

Finger blood flow during period (iii): vibration exposure period

In the control condition without vibration, there were no significant changes in %FBF over the 30 minutes during period (iii) (force without vibration) on either the right hand or the left hand (p>0.1), and there was no significant change in individual median %FBF during period (iii) compared to period (ii) (pre-exposure application of force) (p>0.1).

Within each of the six vibration conditions, the finger blood flow did not vary over the six measurements during any 3-minute vibration exposure at any sensation level (p>0.05), except on the exposed right middle finger with 125-Hz vibration at 25 dB SL (p=0.033) and with 250-Hz vibration at 15 dB SL (p=0.041).

With 8-Hz vibration, the individual median %FBF on both the exposed right hand and the unexposed left hand was reduced with 30 and 40 dB SL vibration compared to period (i) (pre-exposure period) and period (ii) (pre-exposure force period) (p<0.001), but there was no significant change with other sensation levels (-10 dB, -5 dB, 0 dB, 5 dB, 10 dB, 15 dB, 20 dB and 25 dB) (p>0.1). There was a similar pattern in the reduction of finger blood flow with the other five frequencies of vibration: the %FBF was reduced compared to period (i) and period (ii) at 25 dB, 30 dB and 40 dB SL with both 16- and 31.5-Hz vibration (p<0.01) on both hands, from 10 dB to 40 dB SL with 63-, 125- and 250-Hz vibration (p<0.001) on the exposed right hand, from 15 dB to 40 dB SL with 63-, 125- and 250-Hz vibration (p<0.01) on the unexposed left hand, but not with other sensation levels (p>0.05).

With all six frequencies of vibration, there were significantly greater reductions in the median %FBF on both the exposed right hand and the unexposed left hand with each increase in sensation level beyond 30 dB SL with 8-Hz vibration, 25 dB SL with 16- and 31.5-Hz vibration, and 10 dB SL with 63-, 125- and 250-Hz vibration (p<0.05), except between 30 and 40 dB SL with 125-Hz vibration on the exposed right hand (p=0.063). This shows that vibration of the right hand reduced finger blood flow on both hands and that increases in vibration magnitude caused greater reductions in FBF.

The reductions in %FBF on the exposed right hand were significantly greater than those on the unexposed left hand at all sensation levels where there was a significant reduction in finger blood flow on the right hand (p<0.05), except with 8-Hz vibration at 30 dB (p=0.12), 16-Hz vibration at 25 dB (p=0.22) and 30 dB (p=0.33), and 63-Hz vibration at 15 dB (p=0.082).

This shows that the vascular response to vibration was greater on the exposed right hand than on the unexposed left hand.

The %FBF on the exposed right hand did not differ between the six vibration conditions at -10, -5, 0, or 5 dB SL (p>0.1). When the vibration magnitude reached 10 dB SL, there was a lower %FBF with 63-, 125- and 250-Hz vibration than with 8-, 16-, or 31.5-Hz vibration (p<0.05). This difference was also present at 15, 20, 25, 30 and 40 dB SL (p<0.001). On the unexposed left hand the pattern was similar, with lower %FBF during 63-, 125- and 250-Hz vibration than during 8-, 16-, or 31.5-Hz vibration when the vibration magnitude was greater than 15 dB SL (p<0.05). On both the exposed right hand and the unexposed left hand there was a trend for greater reductions in finger blood flow with increasing frequency of vibration at the same sensation level for frequencies from 16 to 125 Hz.

Finger blood flow during period (iv): post-exposure application of force

In the control condition, there was no change in %FBF during period (iv), and there was no difference in individual median %FBF on either the exposed right hand or the unexposed left hand between period (ii) (pre-exposure application of force) and condition (iv) (post-exposure application of force) (p>0.1).

With 8-Hz vibration, there was a progressive increase in %FBF over the 10 measurements during period (iv) (post-exposure application of force) (right: p=0.032, left: p=0.041). With the other five frequencies there was a progressive reduction in %FBF over the ten measurements during period (iv) (right: p<0.001, left: p=0.008).

With 16- to 250-Hz vibration, the median %FBF on both the exposed right hand and the unexposed left hand was lower during period (iv) (post-exposure application of force) than during the last three minutes of period (iii) (vibration at 40 dB sensation level) (p<0.01), except for the unexposed left hand at 63 Hz (p=0.23). In the 8-Hz vibration condition, there was an increase in the median %FBF on both hands during period (iv) compared to the last three minutes of period (iii) (right: p=0.017, left: p=0.011).

Finger blood flow during period (v): recovery period

In the control condition, the individual median finger blood flow on both the exposed right hand and the unexposed left hand during period (v) (recovery period) was significantly less than during period (i) (pre-exposure), during period (ii) (pre-exposure application of force), and during period (iv) post-exposure application of force) (p<0.01).

On the exposed right hand, there was a significant increase in FBF over the 10 measurements of FBF during period (v) (recovery period) after all six frequencies of vibration (p<0.001). On the unexposed left hand, the FBF changed only after 8-Hz vibration (p=0.002) and after 125-Hz vibration (p=0.017).

After exposure to 16 to 250-Hz vibration, the individual median values of %FBF on both hands during period (v) (recovery) were significantly less than during period (i) (pre-exposure) (p<0.05), during period (ii) (pre-exposure application of force) (p<0.001), and during period (iv) (post-exposure application of force) (p<0.01). However, after exposure to 8-Hz vibration, the individual median values of %FBF on both hands during period (v) were less than during period (i) and less than during period (ii) (p<0.001), but greater than during period (iv) (p<0.01).

Relationship between finger blood flow and vibrotactile perception threshold

At sensation levels that significantly reduced finger blood flow, associations between vibrotactile perception thresholds and reductions in FBF on each hand during period (iii) (exposure period) were investigated using the Spearman rank correlation. The *p* value was adjusted for multiple comparisons using the Bonferroni method (Shaffer, 1995). Because the investigation of an association was limited to sensation levels showing significant reductions in finger blood flow, only 24 of the 60 possible correlations (6 frequencies with 10 sensation levels) were performed. The *p*-values for these correlations reported below have been multiplied by 24 to adjust for the multiple comparisons.

For each frequency of vibration, at the sensation levels that caused significant reductions in finger blood flow, the association between %FBF and vibrotactile thresholds were determined. Figure 4 shows an example using thresholds at 63 Hz.

FIGURE 4 ABOUT HERE

There were no significant correlations between the %FBF during vibration exposure and the vibrotactile threshold measured at the same frequency for any of the six vibration frequencies (p>0.05), except for positive correlations on the exposed right hand with 63-Hz vibration at 10 dB SL (p=0.037) and 125-Hz vibration at 10 dB SL (p=0.024).

With low frequency vibration (8, 16 and 31.5 Hz), reductions in FBF on both the exposed right hand and the unexposed left hand were correlated with vibrotactile perception thresholds at high frequencies (63, 125 and 250 Hz). Significant correlations were found at 30 and 40 dB SL with 8-Hz vibration (p<0.01), at 25 dB and 30 dB with 16-Hz vibration (p<0.05) and at 25 dB and 30 dB SL with 31.5-Hz vibration (p<0.05). There were also correlations between reductions in FBF on both hands caused by 16- and 31.5-Hz vibration and thresholds at high frequencies when the vibration magnitude reached 40 dB SL (p<0.05), but these were not statistically significant after adjusting the *p*-value for multiple comparisons. During exposure to high frequency vibration (63, 125 and 250 Hz), reductions in FBF on each hand were not correlated with vibrotactile perception thresholds at either low frequencies (8, 16 and 31.5 Hz) or high frequencies (63, 125 and 250 Hz).

Discussion

Vibrotactile thresholds

The vibrotactile thresholds were highly dependent on the frequency of vibration (Figure 2) but can be separated into two distinct groups. There were high correlations between thresholds at high frequencies (63, 125 and 250 Hz), showing that subjects with a high threshold at any one of these frequencies was likely to have a high threshold at the other two frequencies. This is consistent with the thresholds being mediated by the Pacinian channel at all three frequencies. There were also correlations between thresholds at low frequencies (i.e., at 8, 16 and 31.5 Hz), suggesting thresholds at these frequencies were mediated by a common channel. Thresholds at the high frequencies (63, 125 and 250 Hz) were generally not correlated with thresholds at the low frequencies (8, 16 and 31.5 Hz), indicating that different channels mediated thresholds at low and high frequencies in most subjects. This is consistent with other studies of perception thresholds using the same apparatus and vibration applied to the fingertip (Morioka and Griffin, 2005; Morioka *et al*., 2008).

Finger blood flow during vibration exposure

Acute exposure of the thenar eminence of the right hand to vibration at frequencies from 8 to 250 Hz reduced finger blood flow in both the middle finger of the exposed right hand and the middle finger of the unexposed left hand relative to finger blood flow prior to exposure and finger blood flow during a control condition without vibration. This is consistent with other experimental studies suggesting a neurogenic reflex may be involved in the vascular response of the digital vessels to acute exposures to hand-transmitted vibration (Hyvärinen *et al.*, 1973; Bovenzi *et al.*, 1995; Thompson and Griffin, 2009; Ye and Griffin, 2011a). A greater vasoconstriction on the vibrated right hand is also consistent with previous studies (Bovenzi *et al.*, 2000, 2006; Ye and Griffin, 2011a) and suggests there is also a local mechanism involved in vasoconstriction during exposure to vibration.

Vibration at 63, 125, and 250 Hz provoked statistically significant reductions in finger blood flow when the vibration reached only 10 dB SL (i.e., 10 dB above the threshold for feeling the vibration). With 8-Hz vibration, 30 dB SL was required to provoke statistically significant reductions in finger blood flow, and 25 dB SL was required with both 16- and 31.5-Hz vibration. From 10 to 40 dB SL, a greater reduction in FBF was caused by high frequency vibration (63, 125 and 250 Hz) than by low frequency vibration (8, 16 and 31.5 Hz). Greater reductions in finger blood flow have been found on both exposed and unexposed hands with 125-Hz vibration than with 16-Hz (when using the same frequency-weighted acceleration using the W_h weighting from ISO 5349-1:2001, which differs from the frequency-dependence of vibration thresholds) (Bovenzi *et al*., 2000). With the frequency-weighted acceleration increasing progressively from 0 to 15 ms^{-2} r.m.s., 125-Hz vibration also caused more vasoconstriction than 16-Hz vibration (Thompson and Griffin, 2009). Using vibration with the same subjective severity at each frequency (at sensation levels from 10 dB SL to 40 dB SL), the present study found greater reductions in finger blood flow with high frequency vibration than with low frequency vibration, showing that the acute vascular response to vibration is not solely dependent on the subjective severity of the vibration.

Vasoconstriction increased when the magnitude of vibration applied to a small area of the thenar eminence increased (from 10 to 40 dB SL with the 63-, 125- and 250-Hz vibration, from 25 to 40 dB with 16- and 31.5-Hz vibration, and from 30 to 40 dB SL with 8-Hz vibration). Increased vasoconstriction with greater magnitudes of vibration has been reported with 5.5 to 62 ms^{-2} r.m.s. (unweighted) 125-Hz vibration applied to all fingers (Bovenzi *et al.,* 1999), with 16 to 64 ms^{-2} r.m.s. (unweighted) 125-Hz vibration applied to the intermediate phalanx of the right middle finger (Bovenzi *et al.*, 2004), and progressively increasing magnitudes up to 15 ms^{-2} r.m.s. (weighted) for 16-, 31.5-, 63-, 125-, 250-, and 315-Hz vibration applied to the palm (Thompson and Griffin, 2009). In the previous studies, vibration was applied to various parts of the hand (fingers, palm, and forearm) and the area excited by vibration would have increased as the magnitude of vibration increased. It was therefore not clear whether increased vasoconstriction was caused by the greater magnitude of vibration, the greater area of excitation, or both. Using the same arrangement as the current study (a vibrating probe with a fixed surround) so as to control the area of excitation, a greater reduction in finger blood flow has been found with greater vibration magnitudes (Ye and Griffin, 2011a), as in the present study. Using a similar arrangement to the current study but with two sizes of probe (3-mm and 6-mm diameter) greater reductions in finger blood flow have been found with the greater contact area (Ye and Griffin, 2013).

Finger blood flow after vibration exposure

Finger blood flow on both the exposed hand and the unexposed hand remained reduced after the cessation of vibration, with a greater reduction with increasing frequency of vibration from 8 to 250 Hz. Vasoconstriction after the cessation of vibration has been found previously in fingers of both exposed hands and unexposed hands (e.g., Bovenzi *et al.*, 2004, 2006). Finger blood flow after the cessation of vibration depends on the frequency of vibration, the magnitude of vibration, and the duration of exposure to vibration (Bovenzi *et al.,* 1998, 1999, 2000). With the same frequency-weighted acceleration at both frequencies, a stronger vascular after-effect of vibration (i.e., less finger blood flow and longer recovery period) has been reported after exposure to 125-Hz vibration than after exposure to 16-Hz vibration (Bovenzi *et al.*, 2000). The current study confirmed the existence of persisting after-effects of vibration and showed that they are dependent on the frequency of vibration even when vibration is presented at the same sensation level.

Association between reductions in finger blood flow and vibrotactile perception thresholds

With the higher frequencies of vibration (i.e., 63, 125 and 250 Hz), finger blood flow on the exposed hand was significantly reduced when the magnitude of vibration reached 10 dB SL and it was significantly reduced on the unexposed hand when the magnitude of vibration reached 15 dB SL. Perception thresholds at these frequencies were determined by the response of the Pacinian channel. Studies of masked thresholds show the difference in the sensitivity of the Pacinian channel and the next most sensitive channel (a non-Pacinian channel) is about 30 dB SL (Morioka and Griffin, 2005). The vibration magnitudes provoking significant reductions in finger blood flow (i.e., 10-15 dB SL) were only within the activation zone of Pacinian receptors. This is consistent with previous conclusions that the Pacinian channel is involved in mediating vibration-induced reductions in finger circulation at high frequencies (Ye and Griffin, 2011a, 2013).

The vibration magnitudes used in the present study were determined by the perception thresholds of each individual subject, so although each subject received a different absolute magnitude of acceleration they received vibration with the same sensation level (i.e., the same degree of Pacinian activation when the threshold is mediated by the Pacinian channel). The absence of associations between perception thresholds and reductions in finger blood flow during high frequency vibration is consistent with subjects having a similar degree of vasoconstriction when presented with vibration at the same sensation level. This is as expected if the changes within individual subjects are dependent on their perception threshold at the frequencies where perception is mediated by the Pacinian channel (e.g., 63, 125, and 250 Hz). A previous study has shown that there is an association between perception thresholds and reductions in finger blood flow caused by 125-Hz vibration when the vibration magnitude is not adjusted for the perception threshold of subjects (Ye and Griffin, 2011a).

With the lower frequencies of vibration (i.e., 8, 16 and 31.5 Hz), finger blood flow was not significantly reduced on either hand until the vibration magnitude reached 25 dB SL or greater. Psychophysical studies have shown that with the contact conditions used in the current study the thresholds at these low frequencies are not mediated by the Pacinian channel but by another channel, probably NPI associated with Meissner corpuscles (Bolanowski *et al.*, 1988). The four channel psychophysical model suggests that around 25 dB SL above the absolute thresholds for these frequencies, one or more other channel, including the P-channel, become activated and involved in the mediation of sensations (Bolanowski *et al.*, 1988). The results suggest finger blood flow reduced when the vibration magnitude was sufficient to activate the Pacinian receptors, which occurs at threshold levels at high frequencies but at magnitudes much greater than the threshold at low frequencies.

At high vibration magnitudes (i.e., high sensation levels), there was a positive correlation between thresholds at 125 and 250 Hz and reductions in finger blood flow at low frequencies (i.e., 8, 16 and 31.5 Hz). Although thresholds at low frequencies are determined by the responses of a non-Pacinian channel, other mechanoreceptors become activated at greater magnitudes of vibration (Bolanowski *et al*, 1988; Verrillo *et al*, 2002). At vibration magnitudes 25, 30, and 40 dB SL above the threshold, the Pacinian channel is expected to have been activated. This explains the association between Pacinian and sympathetic response to vibration evident in the circulation system at low frequencies (8, 16, and 31.5 Hz). So, although the Pacinian channel does not mediate sensations caused by low frequencies at magnitudes close to the threshold, it seems to be involved in regulating finger blood flow when the magnitude of low frequency vibration is much greater than the threshold.

Without a surround around a vibrating contactor, as the magnitude of vibration increases the area of skin with a vibration magnitude greater than the threshold of the Pacinian channel will increase. Vasoconstriction increases when the area of excitation increases without any change in the magnitude of vibration (Ye and Griffin, 2013), so without a surround it is unclear whether increased vasoconstriction with increased magnitude of vibration is due to an increased Pacinian response to the greater magnitude, or the increased area of excitation, or both. The fixed surround around the vibrating contactor in the present study was designed to limit the transmission of vibration to other parts of the hand and maintain the same area of excitation with all magnitudes of vibration. If this was successful, the increased vasoconstriction with increased vibration magnitude indicates that in conditions without a surround the greater vasoconstriction with increased magnitude of vibration is due to both the increased area of excitation and the increased Pacinian response with increasing magnitude.

Evaluation of vibration severity

The current international standard for evaluating the severity of hand-transmitted vibration (ISO 5349-1, 2001) uses a frequency weighting W_h to allow for a frequency-dependence in the severity of hand-transmitted vibration. Experimental studies of responses to hand-transmitted vibration show the frequency-dependence varies according to the psychophysical and physiological responses of interest, the magnitude of vibration, and various other factors (Griffin, 2012). Epidemiological studies suggest that frequency weighting W_h may not be optimum for predicting the incidence of vibration-induced white finger from occupational exposures to hand-transmitted vibration, with the weighting underestimating the severity of high frequency vibration relative to the severity to low frequency vibration (Griffin *et al.,* 2003, Bovenzi, 2010, 2012, Brammer and Pitts, 2012).

The present study shows that vasoconstriction provoked by vibration at high frequencies (i.e., 63, 125, and 250 Hz) is related to sensation levels determined by subject absolute thresholds for the perception of vibration, and subjects with greater sensitivity to vibration have stronger vascular responses (Ye and Griffin, 2011a). This suggests absolute thresholds for the perception of hand-transmitted vibration provide a useful indication of the frequency-dependence of vasoconstriction caused by vibration at these higher frequencies. With increasing magnitude of vibration, other mechanoreceptors (e.g., NPII) may be activated and involved in mediating sensations, but there is no clear evidence that this involvement affects peripheral circulation. There are large differences in thresholds between subjects and also differences in thresholds within subjects associated with variations in contact area, contact location, room temperature, etc. The frequency-dependence of these effects cannot be reflected in a single simple frequency weighting.

The acute vasoconstriction provoked by vibration at low frequencies (i.e., 8, 16, and 31.5 Hz) was not related to sensation levels determined by thresholds for the perception of these frequencies of vibration. This might be relevant to the discrepancy in exposure-response relationships for vibration-induced white finger. Standards for predicting the risk of developing vibration-induced white finger employ a frequency weighting based on the frequency-dependence of vibration discomfort, and so will tend to overestimate the vascular effects of low frequency vibration, because the vascular response occurs at magnitudes greater than the threshold for vibration perception at low frequencies. It seems reasonable to assume that different weightings are required to predict sensations (e.g., vibration discomfort), the vascular effects associated with hand-transmitted vibration, and other disorders caused by hand-transmitted vibration.

The findings show that if there is greater sensitivity in the Pacinian channel there is greater vibration-induced vasoconstriction, at least for the magnitudes and frequencies of vibration studied here. The mechanisms mediating this acute response to vibration should not be assumed to be identical to the mechanisms involved in the chronic effects of exposure to vibration (e.g., vibration-induced white finger). However, repeated prolonged vasoconstriction induced by daily occupational exposure to hand-transmitted vibration is unlikely to be beneficial and might be hypothesised as a contributory factor in the development of vibration-induced vascular disorders. In which case, the frequencies of vibration that cause greatest activation of the Pacinian channel would be more likely to cause such disorders, and individuals showing the greatest acute vibration-induced vasoconstriction (e.g., those with lower thresholds) would be more likely to develop such disorders..

Conclusions

Vibration of the thenar eminence at frequencies in the range 8 to 250 Hz reduces finger blood flow in both the hand exposed to the vibration and in the unexposed hand. Vibration at the higher frequencies (63, 125, and 250 Hz) produces vasoconstriction when the magnitude of vibration exceeds the absolute threshold for the perception of vibration. Vibration at the lower frequencies (8, 16, and 31.5 Hz) produces vasoconstriction at magnitudes unrelated to absolute thresholds for the perception of vibration at these frequencies, although still correlated with thresholds at higher frequencies (125 and 250 Hz). The findings are explained by the Pacinian channel mediating the vascular response to vibration in both hands at all frequencies in the range 8 to 250 Hz. At the higher frequencies, the Pacinian channel mediates the perception of vibration at threshold but at the lower frequencies non-Pacinian channels mediate the perception of vibration at threshold and they do not appear to be involved in the regulation of peripheral circulation.

References

Bolanowski SJ, Gescheider GA, Verrillo RT, Checkosky CM (1988) Four channels mediate the mechanical aspects of touch. J Acoust Soc Am, 84: 1680-1694.

Bovenzi M, Griffin MJ, Ruffell CM (1995) Acute effects of vibration on digital circulatory function in healthy men. Occup Environ Med, 52: 834-841

Bovenzi M, Lindsell CJ, Griffin MJ (1998) Duration of acute exposure to vibration and finger circulation. Scand J Work Environ Health, 24(2): 130-137.

Bovenzi M, Lindsell CJ, Griffin MJ (1999) Magnitude of acute exposure to vibration and finger circulation. Scand J Work Environ Health, 25(3): 278-284.

Bovenzi M, Lindsell CJ, Griffin MJ (2000) Acute vascular responses to the frequency of vibration transmitted to the hand. Occup Environ Med, 57: 422-430.

Bovenzi M, Welsh AJL, Griffin MJ (2004) Acute effects of continuous and intermittent vibration on finger circulation. Int Arch Occup Environ Health 77: 255-263.

Bovenzi M, Welsh A J L, Della Vedova A, Griffin M J (2006) Acute effects of force and vibration on FBF, Occup Environ Med, 63: 84 – 91.

Bovenzi M (2010) A prospective cohort study of exposure-response relationship for vibration-induced white finger, Occup Environ Med, 67(1): 38-46.

Bovenzi M (2012) Epidemiological evidence for new frequency weightings of hand-transmitted vibration, Ind Health, 50(5): 377-387.

Brammer AJ and Pitts PM (2012) Frequency weighting for vibration-induced white finger compatible with exposure-response models, Ind Health, 50: 397-411.

Capraro AJ, Verrillo RT, Zwislocki JJ (1979) Psychophysical evidence for a triplex system of mechanoreception. Sens Process, 3: 334-352.

Furuta M, Sakakibara H, Miyao M, Kondo, T, Yamada S (1991) Effect of vibration frequency on finger blood flow. Int Arch Occup Environ Health, 63: 221-224.

Gemne G (1994) Diagnostics of hand-arm system disorders in workers who use vibrating tools. Occup Environ Med, 54: 90-95.

Greenfield ADM, Whitney RJ and Mowbray JF (1963) Methods for the investigation of peripheral blood flow. Br Med Bull, 19: 101-109.

Greenspan JD, Bolanowski SJ (1996) The psychophysics of tactile perception and its peripheral physiological basis. In: L Kruger, ed. Handbook of Perception and Cognition 7: Pain and Touch. Academic Press, San Diego, pp. 25-103.

Griffin MJ, Bovenzi M (2002) The diagnosis of disorders caused by hand-transmitted vibration: Southampton Workshop 2000. Int Arch Occup Environ Health 75: 1-5.

Griffin MJ, Welsh AJL and Bovenzi M (2006) Acute response of finger circulation to force and vibration applied at the palm of the hand. Scand J Work Environ Health, 32(5):383-91.

Griffin MJ (2012) Frequency-dependence of psychophysical and physiological responses to hand-transmitted vibration. Industrial Health, 50, (5): 354-369.

Hyvärinen J, Pyykkö I, Sundberg S (1973) Vibration frequencies and amplitudes in the aetiology of traumatic vasospastic disease. Lancet Issue 7807: 791-794.

International Organization for Standardization (2001) Mechanical vibration – Measurement and evaluation of human exposure to hand-transmitted vibration – Part 1: General Requirements. International Standard, ISO 5349-1.

Morioka M and Griffin MJ (2005) Thresholds for the perception of hand-transmitted vibration: Dependence on contact area and contact location. Somatosensory and Motor Research, 22: 281-297.

Morioka M, Whitehouse DJ, Griffin MJ (2008) Vibrotactile thresholds at the fingertip, volar forearm, large toe, and heel. Somatosensory and Motor Research, 25: 101-112.

Olsen N, Petring OU and Rossing N (1987) Exaggerated postural vasoconstrictor reflex in Raynaud's phenomenon. British Med J, 294.

Takeuchi T, Futatsuka M, Imanishi H and Yamada S (1986) Pathological changes observed in the finger biopsy of patients with vibration-induced white finger. Scan J Work Environ Health, 12:280-283.

Thompson AJL and Griffin MJ (2009) Effect of the magnitude and frequency of hand-transmitted vibration on finger blood flow during and after exposure to vibration. Int Arch Occup Environ Health, 82: 1151-1162.

Verrillo RT (1962) Investigation of some parameters of the cutaneous threshold for vibration. J Acoust Soc Am, 34:1768-1773.

Verillo RT (1963) Effect of contact area on the vibrotactile threshold. J Acoust Soc Am, 35: 1962-1971.

Verillo RT, Bolanowski SJ, Gescheider GA (2002) Effect of aging on the subjective magnitude of vibration, Somatosensory and Motor Research, 19: 238-244.

Ye Y and Griffin MJ (2011a) Reductions in finger blood flow in men and women induced by 125-Hz vibration: association with vibration perception thresholds. J Appl Physol, 111:1606-1613.

Ye Y and Griffin MJ (2011b) Effects of temperature on reductions in finger blood flow induced by vibration. Int Arch Occup Environ Health, 84: 315-323.

Ye Y and Griffin MJ (2013) Reduction in finger blood flow induced by 125-Hz vibration: effect of area of contact with vibration. Eur J Appl Physiol, 113:1017-1026.

Table 1. Vibrotactile perception thresholds and ranges of vibration acceleration applied at each frequency when measuring changes in finger blood flow. Medians and inter-quartile ranges (IQR) of 14 subjects.

Frequency (Hz)	Perception thresholds Median (IQR)	Range of applied acceleration (-10 dB SL to +40 dB SL)	
	Unweighted acceleration (ms^{-2} r.m.s.)	Unweighted acceleration (ms^{-2} r.m.s.)	Frequency-weighted acceleration (ms^{-2} r.m.s.)
8	0.05 (0.03)	0.008 to 13.6	0.006 to 10.2
16	0.07 (0.04)	0.014 to 14.9	0.014 to 14.9
31.5	0.21 (0.11)	0.036 to 51.7	0.009 to 10.3
63	0.34 (0.20)	0.034 to 60.3	0.008 to 15.1
125	0.38 (0.22)	0.038 to 63.7	0.005 to 7.96
250	0.51 (0.31)	0.053 to 98.2	0.003 to 6.13

Figure 1 The sequence of push force and vibration exposure during the five periods of six vibration conditions and the control condition: pre-exposure (period (i)), pre-exposure application of force (period (ii)), vibration (period (iii)) (no vibration in the control conditions), post-exposure application of force (period (iv)), and recovery (period (v)).

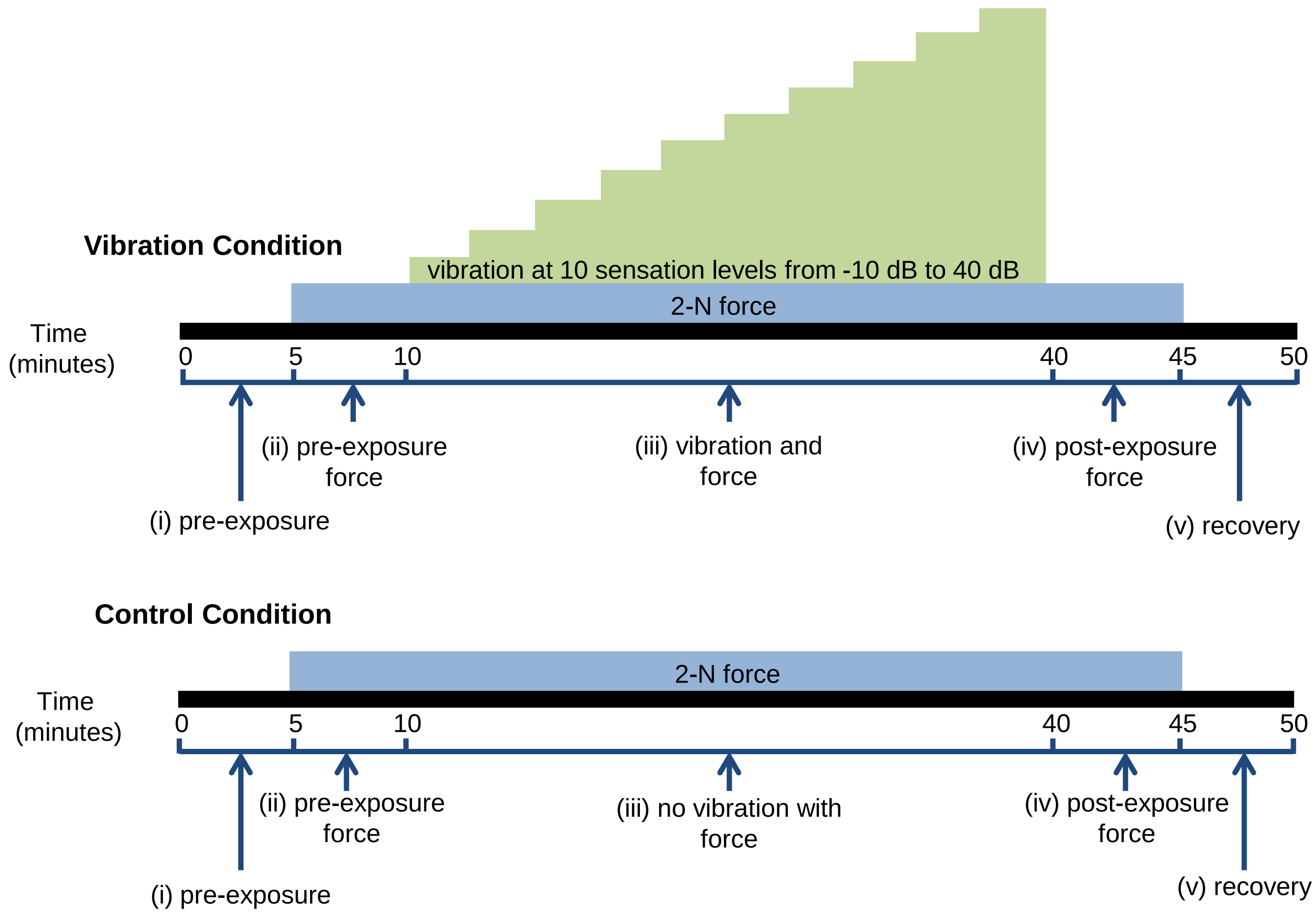

Figure 2 Finger skin temperature on the exposed right middle finger and unexposed left middle finger with vibration at six frequencies (8, 16, 31.5, 63, 125, and 250 Hz) applied to the thenar eminence of the right hand, and during a control condition with no vibration. Medians values from 14 subjects.

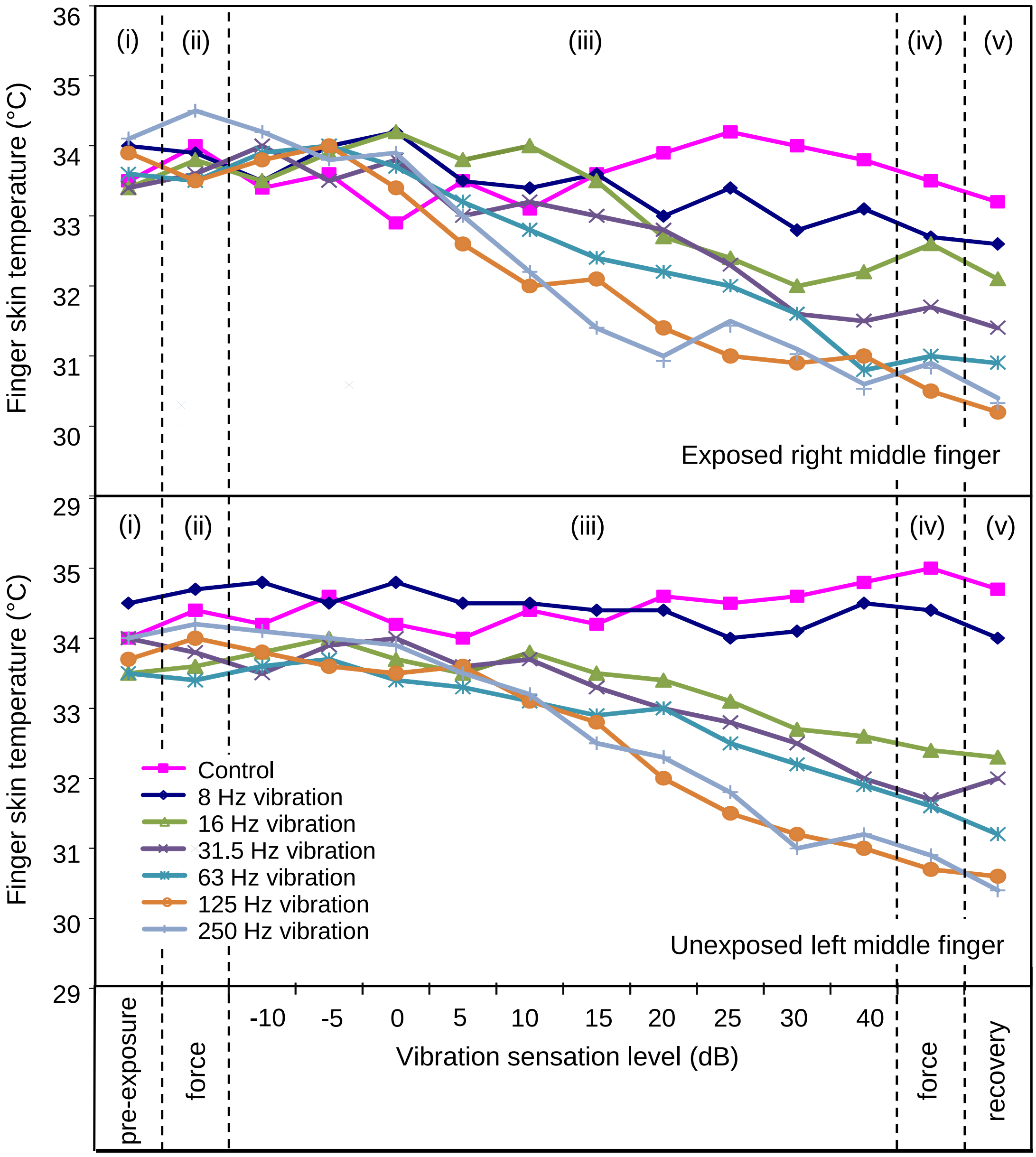

Figure 3 Percentage changes in finger blood flow (%FBF) in the exposed right middle finger and unexposed left middle finger with vibration at six frequencies (8, 16, 31.5, 63, 125, and 250 Hz) applied to the thenar eminence of the right hand and control condition. Median values from 14 subjects.

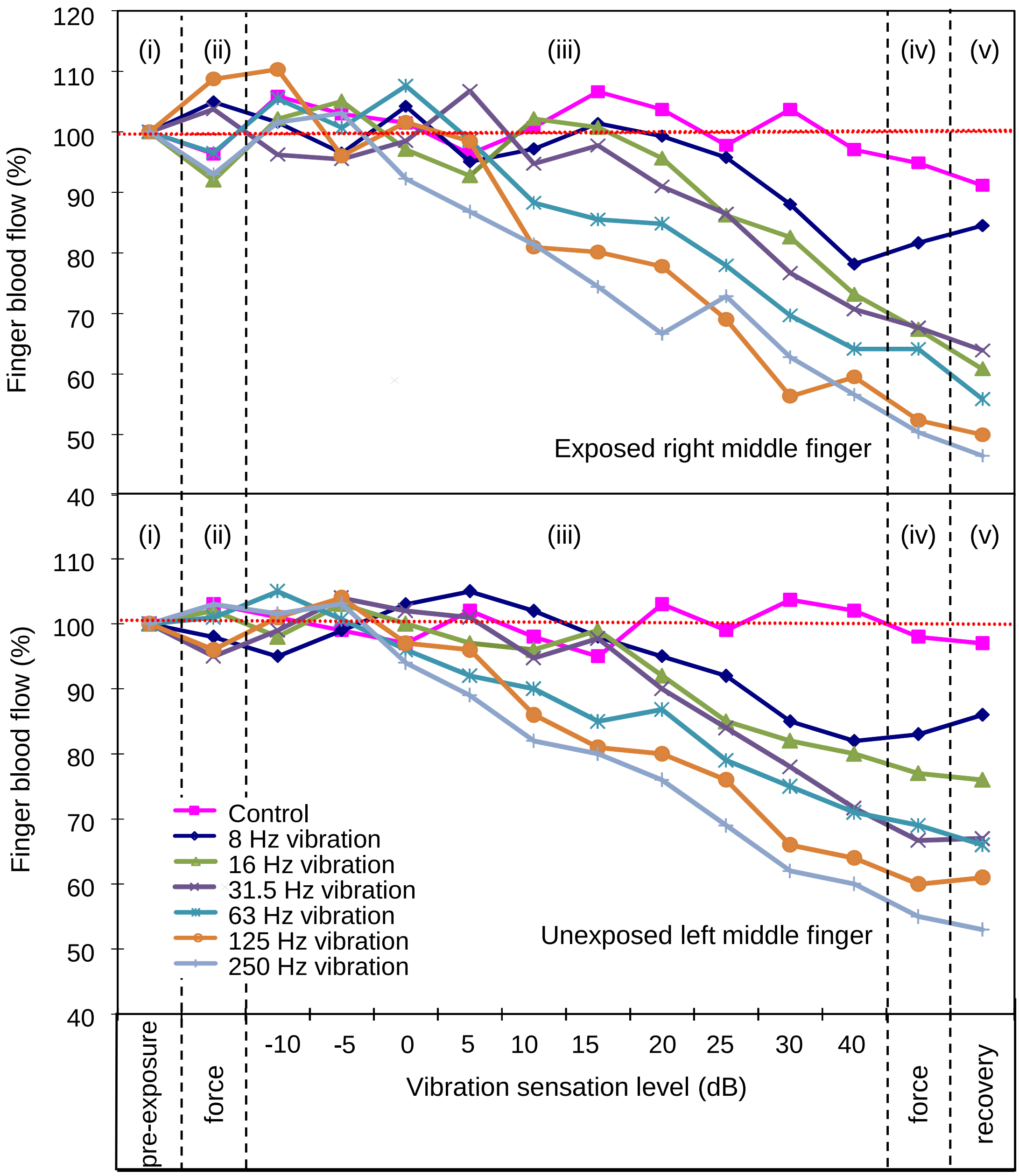

Figure 4 Associations between vibrotactile perception thresholds at 63-Hz and FBF% on the exposed right hand at all sensation levels at which blood flow was significantly reduced during exposure to each frequency of vibration.