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Reductions in finger blood flow induced by 125-Hz vibration: effect of area of contact with vibration

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

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Abstract

To investigate whether the Pacinian channel is involved in vibration-induced reductions of finger blood flow (FBF), vibrotactile thresholds and vasoconstriction have been studied with 125-Hz vibration and two contact areas: 3-mm or 6-mm diameter vibrating probes with 2-mm gaps to fixed surrounds. Fifteen subjects provided thresholds for perceiving vibration at the thenar eminence of the right hand with both contact areas. With both contact areas, FBF was then measured in the middle fingers of both hands during five successive 5-minute periods: (i) no force and no vibration, (ii) force and no vibration, (iii) force with vibration 15 dB above threshold, (iv) force and no vibration, (v) no force and no vibration. Thresholds were in the ranges 0.16 to 0.66 ms^{-2} r.m.s. (6-mm probe) and 0.32 to 1.62 ms^{-2} r.m.s. (3-mm probe). With the magnitude of vibration 15 dB above each individual's threshold with the 3-mm probe, the median reduction in FBF with the 6-mm probe (to 70% and 77% of pre-exposure FBF on the exposed right hand and the unexposed left hand, respectively) was greater than with the 3-mm probe (79% and 85%). There were similar reductions in FBF when vibration was presented by the two contactors at the same sensation level (i.e., 15 dB above threshold with each probe). The findings are consistent with reductions in FBF arising from excitation of the Pacinian channel: increasing the area excited by vibration increases Pacinian activation and provokes stronger perception of vibration and greater vasoconstriction.

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

Introduction

Regular exposure to the vibration of hand-held powered tools can result in a disorder in the fingers commonly called 'vibration-induced white finger', characterised by episodic finger blanching usually triggered by exposure to cold (Gemne *et al.,* 1987; Griffin, 1990; Griffin and Bovenzi, 2002). Evidence of the reversibility of the condition after ceasing exposure to vibration suggests the early stages of the condition may be functional in character (Olsen *et al.*, 1987; Takeuchi *et al.*, 1986; Bovenzi *et al.*, 1995), although the pathogenesis is obscure. Various mechanisms may be involved in disrupting finger blood flow during and after exposure to vibration: central sympathetic reflex mechanisms, locally mediated mechanisms, or a combination of both (e.g., Bovenzi, 1989; Gemne, 1994).

The current International Standard for evaluating hand-transmitted vibration (ISO 5349-1:2001) suggests how the severity of exposures to vibration depend on the magnitude, frequency, direction, and duration of vibration. A series of experimental studies has found that acute exposures to vibration provoke vasoconstriction in the fingers of the vibrated hand and in fingers on the hand not exposed to vibration, with the vascular response during and after exposure dependent on the magnitude and the frequency of the vibratory stimulus in a manner somewhat inconsistent with ISO 5349-1:2001 (Bovenzi *et al.*, 1998, 1999, 2000; Griffin *et al.*, 2006; Thompson and Griffin, 2009). The findings of such experimental studies suggest that finger blood flow is reduced, at least in part, through a sympathetic reflex mechanism.

To understand the mechanisms mediating vibration-induced changes in digital circulation, various other factors need to be taken into account (e.g., the temperature of the environment and the skin, contact conditions). It has been suggested that the grip force and push force applied by the hands to a tool and the area and location of the parts of the hands exposed to vibration influence the changes in circulation caused by hand-transmitted vibration (ISO 5349-1, 2001). However, there has been little study of the influence of the area of contact with vibration or the contact force on vibration-induced reductions of finger blood flow, although the same force applied to different locations on the hand or with different contact areas seems to have different effects on finger blood flow (Bovenzi *et al.*, 2006; Griffin *et al.,* 2006).

Neurophysiological and psychophysical studies suggest there are four types of mechanoreceptors mediating the perception of vibrotactile stimuli in the glabrous skin of the hand (Bolanowski *et al.*, 1988). The receptors are classified according to their

adaptation and receptive field properties: Meissner corpuscles (NP I) are most sensitive to vibration displacement at frequencies between about 4 and 40 Hz, Pacinian corpuscles (P) are most sensitive to vibration displacement at frequencies greater than about 40 Hz, Merkel discs (NP III) are most sensitive to vibration displacement from 0.4 to 4 Hz, and Ruffini endings (NP II) are sensitive to stretching of the skin and function in a similar frequency range to Pacinian corpuscles (Capraro *et al.*, 1979; Bolanowski *et al.*, 1988; Verrillo *et al.*, 2002). Many studies have investigated the effect of contact conditions on absolute thresholds for the perception of vibration and shown that the area of the vibrating probe, the probe shape, the gap between the probe and a fixed surround, and the contact force with the vibrating probe influence thresholds for the perception of vibration (Verrillo, 1962, 1963; Harada and Griffin, 1991; Lindsell, 1997).

Although studies have explored how different probe sizes and contact areas influence psychophysical responses (e.g., absolute thresholds), few studies have considered the effect of contact area on the vascular response to vibration and, with the exception of Ye and Griffin (2011), none have used a surround to control the transmission of vibration to a defined area of skin. By exciting two different areas (using different sizes of vibrating probe and limiting the spread of vibration by two sizes of static surround), the effect of the area of skin excited by vibration on reductions in finger blood flow induced by vibration can be investigated. By applying a vibration magnitude adjusted to the vibration perception threshold of each subject, the relation between the psychophysical response and the vascular response can be studied.

High frequency vibration of the hand produces immediate reductions in finger blood flow, even with magnitudes of vibration close to the threshold for vibration perception. With 250-Hz and 315-Hz vibration applied to the palm of the right hand at 7.8 and 9.4 ms^{-2} r.m.s. (unweighted), respectively, finger blood flow was reduced on both the right hand and the left hand (Thompson and Griffin, 2009). With 125-Hz vibration applied to the thenar eminence of the right hand at 0.5 and 1.5 ms^{-2} r.m.s. (unweighted), the vasoconstriction in both males and females was correlated with the vibration perception threshold, suggesting some form of common mediation in the perception of vibration and the control of finger blood flow (Ye and Griffin, 2011). The perception of low magnitudes of vibration at these frequencies arises from stimulation of the Pacinian channel (Bolanowski *et al*., 1988; Verrillo *et al*., 2002), which has the property of spatial summation giving lower thresholds with larger areas of excitation,

unlike the non-Pacinian channels. It is reasonable to assume that if the Pacinian channel is involved in the control of finger circulation, increasing the area of contact with vibration will increase vibration-induced vasoconstriction as well as reducing vibration perception thresholds.

The objective of this study was to explore the effect of contact area on reductions in finger blood flow induced by hand-transmitted vibration in healthy subjects. The vibration was selected so that it would excite the Pacinian channel and vibrotactile perception thresholds were determined so that exposures to vibration could be related to the degree of excitation in that channel. Finger blood flow and finger skin temperature were measured and used to indicate the peripheral vascular response to vibration. It was hypothesised that with an increase in contact area, vibration applied to the thenar eminence of one hand would produce greater reductions in finger blood flow on both hands.

Methods

Subjects

Fifteen healthy male volunteers gave their written informed consent to participate in the study. Females tend to have lower vibrotactile thresholds than males, and low magnitude vibration tends to produce greater reductions in finger blood flow in females than in males, but the general pattern of vascular changes induced by vibration is similar in males and females (Ye and Griffin, 2011). All subjects were university students with no history of regular use of hand-held vibratory tools in occupational or leisure activities. No subject reported cardiovascular or neurological disorders, connective-tissue diseases, injuries to the upper extremities, or a history of cold hand, and all were non-smokers. The subjects had a mean age of 24.5 (SD: 2.9, range: 18-28) years, stature 175 (SD: 4.7, range: 170-183) cm, weight 76.1 (SD: 9.8, range: 58-85) kg, body mass index (BMI) 24.3 (SD: 2.9, range: 17.6-28.4) $kg.m^{-2}$. From measures of finger length and width and depth at each phalanx with vernier callipers to an accuracy of 0.5 mm, mean finger volumes were calculated as 18.9 (SD: 5.3) cm^3 and 19.2 (SD: 5.6) cm^3 for the middle fingers of the right and left hand, respectively. Subjects avoided consuming caffeine for 2 hours and alcohol for 12 hours prior to testing. The study was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research.

Measurement of vibrotactile perception threshold

Absolute thresholds for perception of vibration were measured using a Vibrotactile Perception Meter (*HVL*ab VPM, University of Southampton) with the von Békésy algorithm. The magnitude of vibration increased or decreased continuously at a constant rate (3dB/s) with the subject pressing a button when vibration was perceived and releasing the button when vibration was not perceived. Thresholds were determined over a minimum of 30 seconds and a minimum of six button presses or releases. Absolute thresholds were expressed as the arithmetic mean of the average peak and the average trough (expressed in ms^{-2} r.m.s.), with the first two judgements ignored.

Thresholds were determined with two different vibrating probes (3 mm and 6 mm diameter), each with a 2-mm gap to a fixed 26-mm diameter circular surround. The flat circular probes were level with the flat circular surrounds. A force of 5 N was applied to the surround. The excitation area was calculated as the area of the probe plus the area of the gap between the probe and the surround, which is the area exposed to the vibration stimulus. The excitation area was 78.5 mm^2 for the 6-mm diameter probe and 38.5 mm^2 for the 3-mm diameter probe.

Measurement of finger blood flow and finger temperature

Finger blood flow (FBF) was measured in the middle finger of both hands by a strain gauge plethysmographic technique. Mercury-in-silicon strain gauges were placed at the base of the finger nails, and plastic pressure cuffs for air inflation were fixed around the proximal phalanges. The pressure cuffs and strain gauges were connected to a plethysmograph (*HVL*ab Multi-channel, University of Southampton).

The FBF was measured with a venous occlusion method. The pressure cuffs were inflated to a pressure of 60 mm Hg (8.0 kPa), and the rises in fingertip volume were detected by means of 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 phalanx of the right and left middle fingers. 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 subjects.

Experimental protocol

The experiment was conducted in a laboratory with a mean air temperature of 25.1 (SD 0.4) ºC.

Each of the 15 subjects attended the laboratory on five occasions, with the order of presentation of conditions balanced over the 15 subjects. In two control conditions, FBF was measured with force applied to the thenar eminence with one of the probe diameters (either 3 mm or 6 mm) with no vibration. In two conditions FBF was measured with force applied to the thenar eminence with one of the probe diameters (either 3 mm or 6 mm) and vibration presented at a magnitude 15 dB above the threshold of the individual subject for that probe diameter. In the fifth condition, FBF was measured with force applied to the thenar eminence with the 6-mm probe diameter and the vibration presented 15 dB above the threshold of the subject for the 3-mm probe diameter. Vibration 15 dB above the threshold was selected so as to trigger a response from the mechanoreceptor of interest (i.e., Pacinian) without activating other channels with higher thresholds than the Pacinian channel. Psychophysical studies have found that with the current conditions (125-Hz vibration applied to the thenar eminence) the threshold of the Pacinian channel is around 30 dB below the threshold of the next most sensitive channel (e.g., Bolanowski et al., 1988).

In each session, finger skin temperature was measured and the experiment proceeded only if the temperature was greater than 30°C. In the first session, thresholds for 125-Hz vibration were then measured three times at the thenar eminence of the right hand of each subject with both the 3-mm diameter probe and the 6-mm diameter probe. The median threshold was calculated and used to calculate the vibration magnitude during finger blood flow measurement.

In each of the five sessions, subjects 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 (Table 1).

TABLE 1 ABOUT HERE

The subjects wore light clothing and lay supine throughout the measurement of FBF 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 at 1-minute intervals. In the first 5-minute measurement period (i), the base-line value of FBF was obtained and then, with the help of the experimenter, subjects applied a downward force of 5 N

with the thenar eminence of their right hand on the applicator of the *HVL*ab Vibrotactile Perception Meter (VPM) and then maintained this force without assistance during periods (ii) to (iv). The hand was in a comfortable posture with all fingers suspended without contact. Visual feedback for the control of downward force was supplied by an analogue display on the control unit of the VPM. During period (iii), sinusoidal vibration was produced in the vertical direction for 5 minutes, followed by a 5-minute period with force and no vibration during period (iv). The right hand was then moved by the experimenter, but maintained at heart height alongside the subject for another 5 minutes during period (v). The left hand was supported at heart level and motionless with no force and no vibration throughout all five periods.

Statistical methods

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 (IQR) as the measures 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 between the five sets of finger blood flow measurements during the 5-minute pre-exposure period, the 5-minute pre-exposure application of force, the 5-minute vibration period, the 5-minute post-exposure application of force, and the 5-minute recovery period. A Wilcoxon matched-pairs signed ranks test was then used to investigate differences between the median finger blood flow during five 5-minute periods and the difference between 5 exposure conditions. A Spearman test was used to test the relation between the contact conditions and FBF reduction induced by vibration at 15 dB above threshold separately.

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

The criterion for statistical significance was $p<0.05$. The p values were adjusted for multiple comparisons.

Results

Vibrotactile perception threshold

The 125-Hz vibrotactile perception thresholds of the 15 subjects were in the range of 0.16 to 0.66 ms^{-2} r.m.s. (median: 0.36 ms^{-2} r.m.s.) with the 6-mm diameter probe and in the range of 0.32 to 1.62 ms^{-2} r.m.s. (median: 0.52 ms^{-2} r.m.s.) with the 3-mm diameter probe. Thresholds measured with the two contact sizes were positively correlated (p=0.027, Spearman) but lower with the larger probe (p<0.001, Wilcoxon; Figure 1).

FIGURE 1 ABOUT HERE

The vibration magnitudes used when measuring finger blood flow (15 dB greater than the threshold) were in the range 0.88 to 3.68 ms^{-2} r.m.s. when determined by thresholds with the 6-mm diameter probe, and in the range 1.80 to 9.17 ms^{-2} r.m.s. when determined by thresholds with the 3-mm diameter probe, with the actual value depending on the subject threshold. These magnitudes correspond to frequency-weighted accelerations in the range 0.11 to 0.46 ms^{-2} r.m.s. and 0.22 to 1.15 ms^{-2} r.m.s. (ISO 5349-1: 2001).

3.2 Room temperature and finger skin temperature

The temperature in the laboratory did not differ during the 25 measurements of finger blood flow within any of the five experimental conditions (median values: 25.1 - 26.0 °C, p>0.1, Friedman). There was no difference in the median room temperature across the five exposure conditions (p>0.1, Friedman).

On neither hand was there a systematic change in finger skin temperature during the 25 measurements of finger blood flow within any of the five experimental conditions (p>0.1; Friedman). There was no differences in finger skin temperature across the five experimental conditions during the pre-exposure period, pre-exposure application of force, vibration exposure, post-exposure application of force, or recovery for either the left or right hand (p>0.133).

Finger blood flow

Finger blood flow was initially expressed as a percentage of the median finger blood flow during period (i), the pre-exposure period (i.e., %FBF). The %FBF varied over the 25-minute period of the two control conditions and the three vibration sessions on both the exposed right hand (Figure 2) and the unexposed left hand (Figure 3).

FIGURES 2 AND 3 ABOUT HERE

Finger blood flow during the pre-exposure period

Finger blood flow did not vary over the five measurements during the 5-minute pre-exposure period on either the exposed hand or the unexposed hand in any condition (p>0.1; Friedman). The individual median FBF over this 5-minute period did not differ across the five conditions on either hand (p>0.1; Friedman), and the FBF did not differ between the exposed right hand and the unexposed left hand in any condition (p>0.1; Wilcoxon).

The finger blood flow was positively correlated with the finger volume (p<0.05, Spearman), except for the right middle finger in condition 1 (p=0.107) and the left middle finger in condition 4 (p=0.081).

Finger blood flow during pre-exposure application of force

Finger blood flow on the exposed and unexposed hands did not change over the five measurements during the pre-exposure application of force in any of the five conditions (p>0.1; Friedman).

On both hands there was a reduction in the median finger blood flow during period (ii) (pre-exposure application of force) compared to period (i) (the pre-exposure period) (p<0.01 on both hands in all five conditions). This shows that the 5-N force applied by the right hand reduced finger blood flow in both hands.

In conditions 2 and 5 with the 3-mm probe, the 5-N force applied by the thenar eminence of the right hand reduced the median blood flow to 76.3% and 74.2%, respectively, in the right middle finger and to 81.3% and 79.6% in the left middle finger. There was no difference in %FBF between the hands during either condition 2 or condition 5 (p>0.1, Wilcoxon).

The finger blood flow in period (ii) (with 5-N force), expressed as a percentage of the FBF in period (i) (no force), differed across the five conditions (p=0.001, Friedman).

In conditions 1, 3, and 4 with the 6-mm probe, the 5-N force reduced the median blood flow to 84.1%, 82.5%, and 85.1%, respectively, in the right hand middle finger (p<0.05, Wilcoxon). The corresponding values for the left middle finger were 90.8% for condition 1 (p=0.054), 88.6% for condition 3 (p=0.031), and 92.4% for condition 4 (p=0.073). The %FBF did not differ across these three conditions (p>0.1, Friedman).

In conditions 1 and 2, there was a trend, not always statistically significant, for a greater reduction in %FBF with the 3-mm probe than the 6-mm probe in both the exposed right hand (p=0.021, Wilcoxon) and the unexposed left hand (p=0.077). Similar results were found on the exposed right hand between conditions 1 and 5

(p=0.055), between conditions 3 and 2 (p=0.033), between conditions 3 and 5 (p=0.018), between conditions 4 and 2 (p=0.044), and between conditions 2 and 5 (p=0.062). However, on the unexposed left hand, a difference in %FBF between the 3-mm and 6-mm probes was only found between conditions 3 and 4 (p=0.037) and between conditions 4 and 5 (p=0.051). All the differences indicate that although the same force was applied to both probes, the 3-mm probe provoked a greater reduction in finger blood flow than the 6-mm probe.

Finger blood flow during vibration exposure

In the two control conditions without vibration (conditions 1 and 2), there were no significant changes in %FBF over the five measurements during period (iii) on either the right or the left hand (p>0.1; Friedman) and there was no change in individual median %FBF compared to period (ii) (pre-exposure application of force) (p>0.1; Friedman).

In the three conditions with vibration (conditions 3, 4, and 5), there were no significant changes in %FBF over the five measurements during period (iii) (force with vibration) on either the right exposed hand or the left unexposed hand (p>0.05; Friedman), except the right hand in condition 3 (p=0.011; Friedman). On both hands, there were significant reductions in the individual median %FBF during period (iii) (force with vibration) compared to period (i) (pre-exposure period) (p<0.001; Wilcoxon) and compared to period (ii) (pre-exposure force period) (p<0.001; Wilcoxon) for all three conditions. This shows that vibration of the thenar eminence of the right hand reduced finger blood flow in both hands. There was a greater reduction in %FBF in the exposed right hand than the unexposed left hand in all three conditions (p<0.01, Wilcoxon).

Individual FBFs in the exposed right hand during period (iii) (i.e., force and vibration) were also expressed as percentages of the finger blood flow during period (ii) (i.e., force without vibration) and are referred to as $\%FBF_v$. The $\%FBF_v$ reduced to 81.2% in the exposed right hand and 85.2% in the unexposed left hand during condition 3, to 70.2% in the right hand and 77.3% in the left hand during condition 4, and to 79.2% in the right hand and 83.9% in the left hand during condition 5.

The individual values of $\%FBF_v$ on the exposed right hand are compared between conditions 3 and 4 in Figure 4(a) (showing the effect of vibration magnitude with constant probe size), between conditions 3 and 5 in Figure 4(b) (showing effect of both probe size and vibration magnitude: 15 dB above threshold with 3-mm and 6-

mm probes), and between conditions 5 and 4 in Figure 4(c) (showing the effect of probe size with constant magnitude vibration).

FIGURE 4 ABOUT HERE

Individual median values of $\%FBF_v$ were correlated between conditions 3 and 4 (p=0.011, Spearman), between conditions 4 and 5 (p=0.001), and between conditions 3 and 5 (p=0.008) in the exposed right hand. In the unexposed left hand, the values of $\%FBF_v$ were correlated between conditions 4 and 5 (p=0.027) and between conditions 3 and 5 (p=0.044), but not between condition 3 and 4 (p=0.097).

The $\%FBF_v$ was lower (on both the right and the left hand) in condition 4 compared to condition 3 (Figure 4(a)) (p<0.01, Wilcoxon), indicating that 125-Hz vibration with the 6-mm probe provoked a greater reduction in finger blood flow when presented 15 dB above the threshold with the 3-mm probe than when presented 15 dB above the threshold with the 6-mm probe.

The $\%FBF_v$ was lower (on both the right and the left hand) in condition 4 compared to condition 5 (Figure 4(b)) (p<0.01, Wilcoxon), indicating that 125-Hz vibration presented 15 dB above the threshold with the 3-mm probe provoked a greater reduction in finger blood flow with the 6-mm probe than with the 3-mm probe.

The $\%FBF_v$ did not differ (on either the right or the left hand) between conditions 3 and 5 (Figure 4(c)) (p>0.05, Wilcoxon), indicating that 125-Hz vibration 15 dB above threshold with two different contact conditions induced similar vasoconstriction.

Finger blood flow during post-exposure application of force

In the three conditions with vibration, but not the two conditions without vibration, there were significant changes in %FBF over the five measurements during period (iv) (post-exposure application of force) (p<0.001; Friedman).

In the two conditions without vibration, there were no significant differences in individual median %FBF on either hand between period (ii) (pre-exposure application of force) and condition (iv) (post-exposure application of force) (p>0.1; Wilcoxon).

In the three conditions with vibration, the median %FBFs on both the right and the left hand were lower during period (iv) (post-exposure application of force) than during period (ii) (pre-exposure application of force) (p<0.01, Wilcoxon).

Finger blood flow during the recovery period

In all five conditions, there were significant changes in %FBF in both the right and the left hand during the five measurements in period (v) (recovery period) (p<0.001; Friedman).

In conditions 1 and 2 (without vibration), on both hands the individual median %FBF (expressed as percentage of FBF during period (i)) was less during period (v) (recovery) than during period (i) (pre-exposure) (p<0.05; Wilcoxon), but greater than during period (ii) (pre-exposure application of force), period (iii) (exposure period), and period (iv) (post-exposure application of force) (p<0.001; Wilcoxon).

In conditions 3, 4 and 5 (with vibration), on both hands the individual median finger blood flow during period (v) (recovery) was significantly less than during period (i) (pre-exposure) and during period (ii) (pre-exposure application of force) (p<0.05; Wilcoxon) but significantly greater than during period (iii) (vibration exposure) and period (iv) (post-exposure application of force) (p<0.01; Wilcoxon).

Discussion

Finger blood flow during application of static force

The reduction in finger blood flow caused by a 5-N force may be expected to depend on both the location and the area of the contact with the hand. In this study, force applied to the thenar eminence of the right hand reduced finger blood flow in the middle finger of the right hand and the middle finger of the left hand with both contact conditions. A greater reduction in finger blood flow was found with the smaller probe (3-mm probe with 2-mm gap). A previous study found that applying a 5-N force with the medial phalanx of a finger on the right hand to a 40 by 20 mm surface reduced FBF in the exposed finger, with no significant changes in an unexposed finger on the left hand (Bovenzi *et al.*, 2006). Although the same force was used, the contact location differed and the different contact area will have changed the contact pressure. In the present study, when the same 5-N force was applied to the thenar eminence of the right hand in period (ii) with two different probe areas (7.06 mm^2 and 28.26 mm^2), the pressure with the smaller contact area (0.7 N/mm^2), was approximately four times greater than the pressure with the larger contact area (0.18 N/mm^2). This difference may have provoked the greater vasoconstriction in digits on the exposed right hand during period (ii).

Finger blood flow during vibration exposure

The bilateral reductions in finger blood flow caused by 125-Hz vibration applied to a small area of one hand at magnitudes in the range 0.88 to 9.17 ms^{-2} r.m.s. (i.e., 0.11 to 1.15 ms^{-2} r.m.s. frequency-weighted) are consistent with a previous study with 125-Hz vibration at 0.5 and 1.5 ms^{-2} r.m.s. (Ye and Griffin, 2011). Vibration at 0.5 and 1.0 ms^{-2} r.m.s. (frequency weighted) has also be reported to reduce finger blood flow with 250-Hz and 315-Hz vibration, but with no significant reduction with these magnitudes at frequencies between 16 Hz and 125 Hz (Thompson and Griffin, 2009). Somewhat different experimental conditions and a greater number of finger blood flow measurements at each magnitude may have provided greater power to detect small changes in the present study.

Condition 4 used the same 6-mm probe with 2-mm gap as condition 3, but the vibration magnitude was increased from 15 dB above the threshold with the 6-mm probe to 15 dB above the threshold with the 3-mm probe) (i.e., increased from the range 0.88 - 3.68 ms^{-2} r.m.s. to the range 1.8 - 9.17 ms^{-2} r.m.s.). This reduced the median %FBF from 81% to 70% in the exposed right hand and from 85% to 77% in the unexposed left hand. Stronger vasoconstriction in both hands with greater vibration magnitudes has previously been reported with 125-Hz vibration in the ranges 5.5 to 62 ms^{-2} r.m.s. (Bovenzi *et al.*, 1999) and 16 to 64 ms^{-2} r.m.s. (Bovenzi *et al.*, 2004). With vibration magnitudes increasing from 0 to 15 ms^{-2} r.m.s. (frequency-weighted) finger blood flow reduces progressively (Thompson and Griffin, 2009). With similar vibration excitation to the present experiment (6-mm probe) increased vasoconstriction has been found in both hands as the magnitude of 125-Hz vibration increased from 0.5 to 1.5 ms^{-2} r.m.s. (Ye and Griffin, 2011).

Condition 5 used the same vibration magnitude as condition 3 (15 dB above threshold determined with 3-mm probe) but with a 6-mm probe and not a 3-mm probe. This reduced the %FBF from 79% to 70% in the exposed right middle finger and from 84% to 77% in the unexposed left middle. The increased probe diameter increased the excitation area from 38.5 mm^2 to 78.5 mm^2). There are no known studies of the effect of the area of vibration excitation on reductions in finger blood flow, but it is possible to compare the vasoconstriction obtained in different studies with different areas of excitation. Vibration of the whole hand with 125 Hz at 62 ms^{-2} r.m.s. has reduced %FBF to 25% (Bovenzi *et al.*, 1999), whereas vibration of only the palm on a 40 mm by 20 mm platform with 125-Hz at 64 ms^{-2} r.m.s. reduced %FBF to only 70% (Griffin *et al.*, 2006). Although conducted with different subjects and

different methods, the findings are consistent with greater areas of excitation triggering a greater vascular response.

Reductions in finger blood flow on fingers of the unexposed hand as well as the exposed hand is also consistent with previous studies (Bovenzi *et al.*, 2000, 2006; Thompson and Griffin, 2009; Ye and Griffin, 2011). It has previously been hypothesised that vibration reduces finger blood flow through a sympathetic reflex mechanism provoking vasoconstriction in both hands. The extent of vasoconstriction during and after vibration depends on the frequency of vibration – with greater vasoconstriction at higher frequencies when using frequency-weighted acceleration (i.e., the same velocity at all frequencies) (Bovenzi *et al.*, 2000; Thompson and Griffin, 2009). The results of these studies agreed with the neurophysiological evidence that vibration in the range 63 to 500 Hz can stimulate skin mechanoreceptors such as Pacinian corpuscles, which could represent the afferent branch of the sympathetic reflex arch elicited by vibration.

Several studies have concluded that when perception is mediated by the Pacinian channel the vibrotactile perception thresholds decrease with increasing contact area, due to the property of 'spatial summation' (Verrillo, 1968). Vibrotactile thresholds at 125 Hz also reduce when the contact area is increased from the fingertip to the whole hand (Morioka and Griffin, 2005). Using apparatus similar to that employed in the present study, thresholds at the fingertip with a 1-mm diameter circular probe (with 1-mm gap to a fixed circular surround) and a 6-mm diameter circular probe (with 2-mm gap to a fixed circular surround) were lower with the larger contactor (Morioka *et al.*, 2008). With the larger contact area the excitation area increased and, in accord with 'spatial summation', more Pacinian corpuscles would be activated resulting in a lower threshold. According to the spatial summation theory, a 3 dB decrease is expected in the Pacinian threshold per doubling of contact area (Verrillo, 1963), so an increase in the excitation area from 38.5 to 78.5 mm^2 (a factor of 2) was expected to produce a 3 dB decrease in threshold. In present study, the median reduction in the threshold across subjects was 2.87, consistent with spatial summation in the Pacinian channel.

Individual reductions in FBF provoked by 125-Hz vibration have been found to be correlated with individual thresholds for perceiving 125-Hz vibration, suggesting the Pacinian system is involved in reducing FBF (Ye and Griffin, 2011). For the present study, this suggested there would be greater reductions in FBF when the perception of vibration is mediated by the Pacinian channel. Spatial summation in the 125-Hz

thresholds in this study is consistent with the P channel mediating vibration perception, as expected for the contact conditions and the magnitudes of 125-Hz vibration employed, and from the four channel model of vibrotactile perception (Bolanowski *et al.,* 1988) and various psychophysical experiments (Verrillo, 1968; Morioka and Griffin, 2005; Morioka *et al.*, 2008). It seems reasonable to conclude that the reduction in FBF with increased contact area was primarily due to the spatial summation characteristics of the P channel. The similar reduction in FBF when exposed to vibration at the same sensation level (15 dB above threshold with different probe sizes) is further evidence for the role of the Pacinian channel. The results are therefore consistent with the vibration-induced reductions in FBF found here being determined by activation of the Pacinian channel, with the extent of the reduction being determined by the sensation level rather than the absolute magnitude of vibration. The findings are also consistent with vibration eliciting a central sympathetic reflex through activation of Pacinian mechanoreceptors.

Conclusions

With increased area of contact with 125-Hz vibration applied to the thenar eminence, vibrotactile thresholds reduce and vibration-induced vasoconstrictions increase. For 125-Hz vibration presented with different contact areas, there are similar reductions in finger blood flow when the sensation level is the same. The findings are consistent with reductions in finger blood flow arising from excitation of the Pacinian channel: a doubling of the area of contact with vibration increases Pacinian activation (i.e., spatial summation) and increases vibration-induced vasoconstriction in fingers on a hand exposed to vibration and on the hand not exposed to vibration.

Conflict of interest The authors declare that they have no conflict of interest.

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Table 1 Vibration conditions

Condition	Probe diameter (mm)	Exposure period					
		(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	Force (N)	Force (N)
1	6	0	5	5	0	5	0
2	3	0	5	5	0	5	0
3	6	0	5	5	15 dB above threshold with 6-mm contactor	5	0
4	6	0	5	5	15 dB above threshold with 3-mm contactor	5	0
5	3	0	5	5	15 dB above threshold with 3-mm contactor	5	0

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Figure 1 Individual 125-Hz thresholds at the thenar eminence of the right hand determined with 6-mm and 3-mm diameter probes.

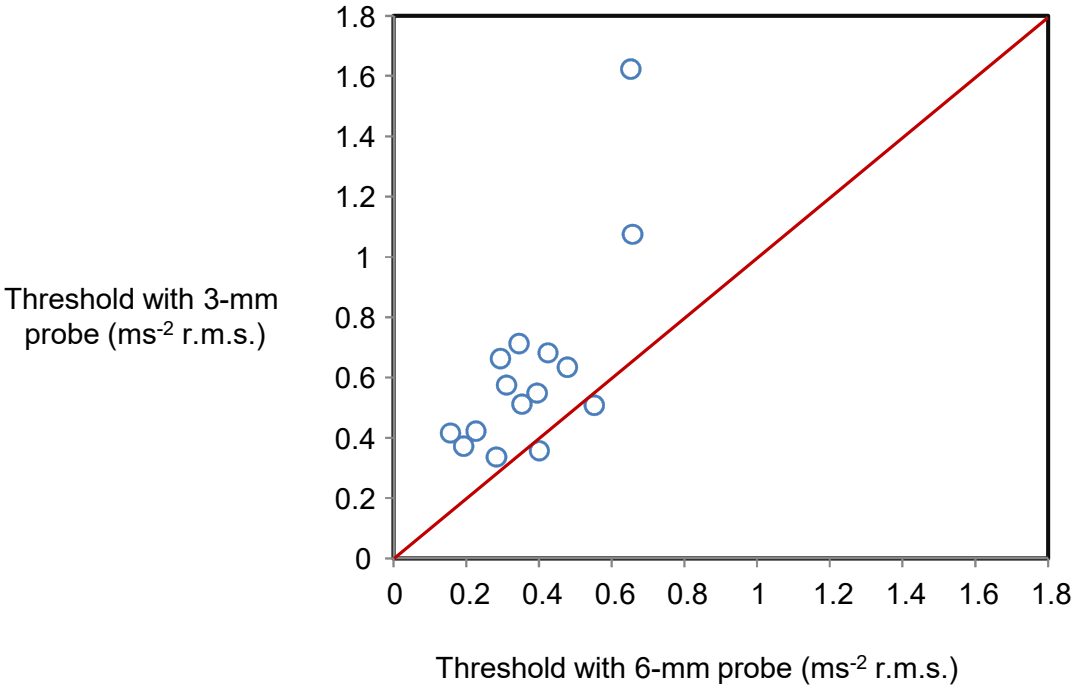

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Figure 2 Percentage changes in finger blood flow (%FBF, calculated from the FBF in period (i)) in the exposed right middle finger during conditions with and without vibration.

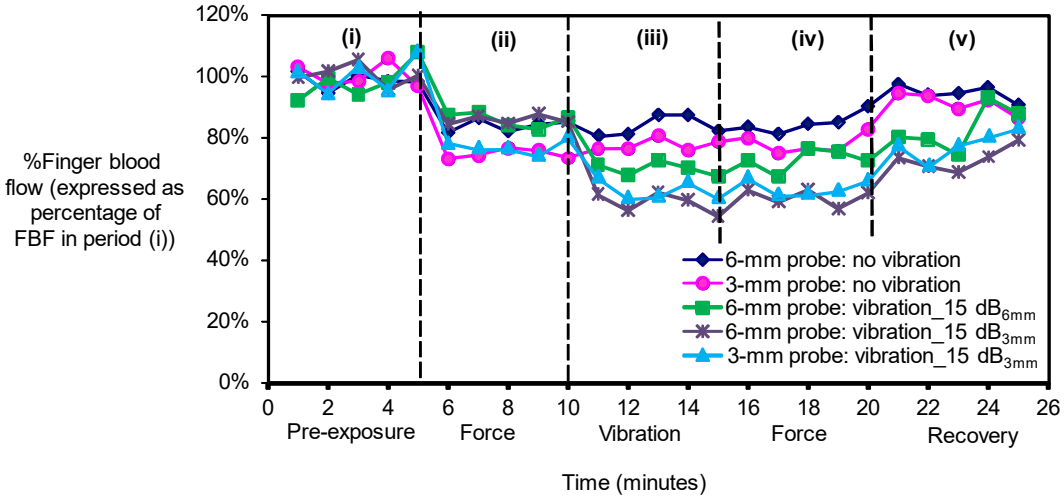

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Figure 3 Percentage changes in finger blood flow (%FBF, calculated from the FBF in period (i)) in the unexposed left middle finger during conditions with and without vibration.

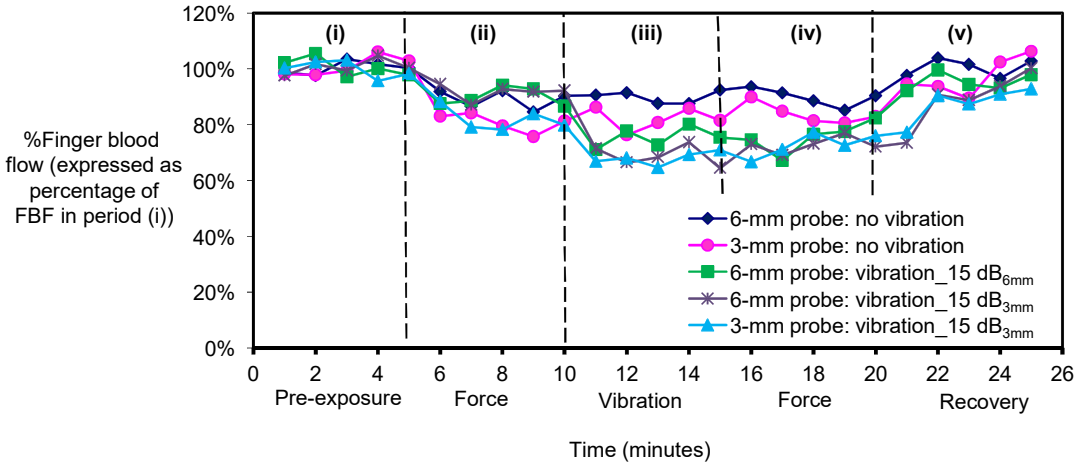

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Figure 4 Individual finger blood flow in the exposed right hand during vibration in period (iii) expressed as a percentage of blood flow during period (ii) (i.e., $\%FBF_v$) with three vibration conditions: (a) Comparison between condition 4 and condition 3; (b) Comparison between condition 5 and condition 3; (c) Comparison between condition 4 and condition 5.