Bull Yamaguchi Med Sch 65(1-2):11-20, 2018

Concomitant Changes and Response Patterns in Finger Vibrotactile Perception and Blood Flow Induced by Acute Exposure to Hand-Arm Vibration

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(Received October 12, 2017, accepted April 13, 2018)
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Abstract **Purpose:** The main purpose was to investigate the concomitant changes and response patterns in finger vibrotactile perception threshold (VPT) and finger blood flow (FBF) induced by acute exposure of healthy subjects to hand-arm vibration (HAV). **Methods:** Four right fingers of ten subjects were randomly exposed to vibration (31.5 Hz and 125 Hz with a frequency-weighted acceleration of 5.5 m/s^2 rms) or no vibration for 5 min. Pre- and post-exposure FBF and VPT in the exposed fingers were measured. **Results:** Compared to corresponding before-exposure values, vibration exposure only under 125 Hz condition caused significant increase in VPT in both index and little fingers at both 31.5 Hz and 125 Hz test frequencies. Also, exposure to acute vibration prevented significant reductions in FBF revealed for the control condition under both vibration exposure conditions, and led to a non-significant increase in FBF under125 Hz exposure condition. **Conclusions:** VPT responses to the current magnitude of vibration were probably predominantly mediated by the Pacinian mechanoreceptors. Acute exposure to HAV may prevent vasoconstriction resulting from the push force exerted by the exposed fingers.

Key words: Hand-arm vibration, acute exposure, vibrotactile perception, blood flow, human fingers

Introduction

In previous research works with exposure of human hands to acute hand-arm vibration (HAV), it has been demonstrated that such exposure causes stimulations of skin mechanoreceptors that are reflected by the changes in finger vibration perception representing the relevant mechanporeceptors.[1-3] On the other hand, stimulation of skin mechanoreceptors by vibration triggers central sympathetic reflexes and subsequent changes in finger circulation.[4] As understandable, a close relationship exists between the changes in perception of skin mechanoreceptors mediating vibration and vibration-induced changes in finger circulation.[3] However, most of the previous studies were conducted with either measurements of vibration-induced changes in vibrotactile perception of various mechanoreceptors or finger circulation in different subjects, not with both of those measurements in the same study among the same subjects.[2,4-9] Concomitant measurements of

vibrotactile perception representing various mechanoreceptors and finger circulation in the same subjects exposed to acute HAV should help to better understand the relationship between mechanoreceptor perception of vibration and finger circulation and the underlying mechanisms behind the observed changes in those parameters.

Among the skin mechanoreceptors, the Pacinian corpuscles respond to vibration at frequencies between 40 to 400 Hz and Meissner corpuscles, at frequencies below 40 Hz.[10] Therefore, in the literature, vibration exposure frequencies like 31.5 Hz and 125 Hz have been used to stimulate Meissner and Pacinian corpuscles, respectively.[2,6] In the present study, we sought to characterize the changes in the vibrotactile perception threshold (VPT) of skin mechanoreceptors and blood flow in human fingers induced by acute exposure of healthy subjects to HAV of two different commonly used frequencies, 31.5 Hz and 125 Hz, but with the same energy-equivalent frequency-weighted acceleration. We hypothesized that exposure to vibration of same frequency-weighted acceleration but at the lower frequency (31.5 Hz) would cause changes in VPT mainly of the Meissner mechanoreceptors and at the higher frequency (125 Hz), mainly of the Pacinian mechanoreceptors. Also, such exposure to vibration would cause changes in finger blood flow (FBF) that will correspond to the observed responses in skin mechanoreceptors mediating vibration.

In the literature, the patterns of vibration-induced acute changes in FBF are contradictory: a number of studies showed vasoconstriction from acute exposure of subjects to HAV while some others demonstrated vasodilation from such exposure.[11] Therefore, another purpose of this study was to ascertain the pattern of responses (vasoconstriction or vasodilation) in FBF induced by acute exposure of healthy subjects to HAV.

According to the international standard ISO 5349-1 (2001), the frequency weighting W_h for vibration of the same magnitude (i.e. frequency-weighted acceleration) should induce same physiological responses irrespective of the vibration exposure frequencies.[12] Therefore, we further hypothesized that the observed responses in VPT and FBF induced by acute exposure to HAV will follow the changes mentioned in the international standard ISO 5349-1 (2001).

Materials and Methods

Subjects

In this study, 10 (5 males and 5 females) healthy nonsmoking normotensive young volunteers were recruited. Their demographic characteristics are shown in Table 1. The subjects were free from any known vascular or neurological diseases. An oral explanation of the test procedure of the study was made to all of them. All the subjects underwent a practice session to familiarize themselves with the experiment protocol including various measurements. The subjects were instructed to refrain from eating and drinking tea or coffee for at least 2 h and smoking and alcohol drinking for 12 h, and to avoid all medications for 3 days prior to the beginning of the test. During the experiment, they put on four items of light clothing (two each for

Table 1 Demographic characteristics of study participants (N=10). Values are shown as median (IQR)

Charactersistics	Median (IQR)
Age (years)	20.0 (0.5)
BMI (kg/m^2)	20.7 (3.9)
Hand (right)	
Length (cm)	17.7 (2.0)
Circumference (cm)	19.4 (3.0)
Index finger (right)	
Length (cm)	6.8 (0.8)
Circumference (cm)	5.9 (1.0)
Middle finger (right)	
Length (cm)	7.5 (0.8)
Circumference (cm)	5.8 (0.8)
Ring finger (right)	
Length (cm)	7.0 (1.0)
Circumference (cm)	5.5 (0.7)
Little finger (right)	
Length (cm)	5.8 (1.2)
Circumference (cm)	4.9 (0.7)

the upper and lower parts of the body) and socks. This study was conducted in the winter season (December 2016 - January 2017) between 9 am to 6 pm.

Experimental design

The experimental protocol has been shown schematically in Fig. 1. After arrival to the temperature-controlled experiment room (room temperature, 25 ± 1℃), the participants were seated on a chair. At the beginning of each experimental session, skin temperature was measured at the distal fingers of the test hand. The subjects' hands were warmed using a heater if their finger skin temperature was less than 28℃. After ensuring stable finger skin temperature, the subjects rested comfortably without any stress placing both hands on their thighs. They used an electronic noise-canceling headphone (Quiet Comfort 35, Bose, USA) to protect themselves from the noise of the vibration generator. At the end of acclimatization for 20 min, the subjects placed the right hand approximately at heart level, palm down over hard foam padding for the measurements of FBF. After a rest period of 1 min, pre-exposure FBF was recorded at the dominant hand (all right). Then following a rest-period of 1 min, pre-exposure measurements of VPT were performed. After this, the subjects rested for further 1 min and then were instructed to place their 4 fingers (except thumb) of the dominant hand on a wooden platform mounted on the vibrator as shown in Fig. 1. They were exposed to one of the three exposure conditions conducted on 3 different days and randomized for each subject: control (no vibration), and vibration at 31.5 Hz and 125 Hz. The weighted acceleration of generated vibration was 5.5 m/s^2 rms.[4] During exposure, the subjects exerted a downward force of about 2 N on the wooden platform. After cessation of exposure, subjects' hands were gently moved with help from the experimenter. This was followed by post-exposure measurements of FBF and VPT. The control condition was identical to the other two conditions except that no vibration was generated during exposure while placing the fingers on the wooden platform.

Equipment and measurements

The wooden platform (size: 8 cm x 10 cm) was mounted on the vibratory plate of an electromagnetic shaker (MEE 65, Akashi, Japan), which was connected to a computer-controlled power amplifier (S.DA 07, Akashi, Japan) and controller (9991, Akashi, Japan). A pick-up (V301 SB, Akashi, Japan) was rigidly fitted to the vibrator to monitor the controlled vibration exposure from it. The vibration level of the wooden platform was confirmed by an accelerometer (PV-97C, Rion, Japan) mounted on it and connected to a 3-axis vibration meter (VM-54, Rion, Japan). To display downward force on the wooden platform, load cells (LMA-A-5N-P, Kyowa, Japan) were fixed between the wooden platform and the vibrator, and were connected to a strain indicator (CDV-700A, Kyowa,

a: Measurement of finger skin temperature
a-b: Acclimatization (20 min)
b-c: Rest (1 min)
c-d: Baseline measurement of FBF (40 sec approx.)
d-e: Rest (1 min)
e-f: Baseline measurement of VPT at 3 test frequencies (7 min approx.)
f-g: Rest (1 min)
g-h: Exposure (control, 31.5 Hz or 125 Hz condition; 5 min)
h-i: After-exposure measurement of FBF (40 sec approx.)
i-j: After-exposure measurement of VPT (7 min approx.)

B

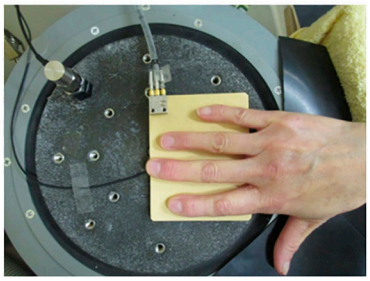

Fig. 1 The schematic experimental protocol (A, upper left) and subject's hand-posture during exposure (B, lower right).

Japan). Finger skin and room temperature was measured by using digital thermistors (SZL-64, Technol seven, Japan) with a measurement accuracy of ±0.15℃, connected to a scanner (X115, Technol seven, Japan) and high accurate data logger (K730, Technol seven, Japan).

FBF was recorded from the dorsal side of fingers by using the Laser Speckle Flowgraphy (LSFG; Softcare, Fukutsu, Japan). LSFG can noninvasively measure the real-time skin blood flow as the relative velocity of the red blood cells moving through the vessels of the skin. This measurement modality is based on the fluctuation in the random interference pattern (speckle pattern) of laser light reflected from the tissues that is captured by a charge coupled device (CCD) camera.[13] The blood flow value used in LSFG system is a relative value expressed in arbitrary units as Mean Blur Rate (MBR). During recording of FBF, subjects were asked to breathe gently and not to move the body or hands.

VPT (expressed in m/s^2) was measured at the fingertips of right index and little fingers using a commercially available Vibrotactile Perception Meter, VPM (HVLab, University of Southampton, UK). VPT was measured at three randomized test frequencies (4 Hz, 31.5 Hz, and 125 Hz) following the protocol mentioned in the international standard ISO 13091-1 (2001).[14]

Ethical approval

The protocol of the present study was approved by the institutional review board of Yamaguchi University School of Medicine (approval no. H26-57).

Statistical analyses

FBF values (MBR) recorded from the entire length of the dorsal side of fingers except the nail region were used for the analysis. The VPT values obtained from the index and little fingers were transformed to dB (relative 10^{-6} m/s^2). The FBF and VPT data did not follow a normal distribution, and are shown as median and interquartile range (IQR) in the figures. The data were analyzed using Wilcoxon signed-ranks test for two-related samples and Friedman test for multiple-related samples as appropriate. The IBM SPSS statistical software version 22.0 (IBM SPSS Statistics, IBM Corporation, USA) was used for analysis of the data. Statistical significance was set at a 2-sided value of $P < .05$.

Results

The values of VPT obtained before and after exposure to various test conditions at different test frequencies in index and little fingers are shown in Fig. 2. In general, the before-exposure values of VPT in both fingers increased as the test frequency increased. However, comparison between the before-exposure values for each finger at 3 test frequencies did not reveal any significant differences between those ($P > .05$; Friedman test). Compared to the corresponding before-exposure values, no significant change in VPT was observed after exposure under the control condition at any test frequency in the index or little finger. Similar findings were observed under the exposure condition of 31.5 Hz except that the after-exposure value at the little finger was significantly higher at the test frequency of 125 Hz when the before- (median 107.8 dB, IQR 18.0 dB) and after-exposure (median 113.0 dB, IQR 17.9 dB) values were compared ($P < .05$; Wilcoxon signed-ranks test). On the other hand, under the exposure condition of 125 Hz, VPT in both fingers increased significantly after exposure at the test frequencies of both 31.5 Hz (median and IQR values before and after exposure were 101.6 dB and 8.0 dB, and 106.7 dB and 8.9 dB for the index finger, and 104.1 dB and 11.3 dB, and 107.0 dB and 10.6 dB for the little finger, respectively) and 125 Hz (median and IQR values before and after exposure were 104.8 dB and 11.5 dB, and 116.6 dB and 15.3 dB for the index finger, and 108.8 dB and 18.1 dB, and 114.1 dB and 15.4 dB for the little finger, respectively) ($P < .05$ to .01; Wilcoxon signed-ranks test), but not at the test frequency of 4 Hz (Fig. 2).

Fig. 3 represents the values of FBF obtained before and after exposure from all fingers. The baseline values did not differ significantly when the values obtained under three test conditions were compared for each finger ($P > .05$; Friedman test). Comparison of the before- and after-exposure values revealed a significant decrease in FBF for the

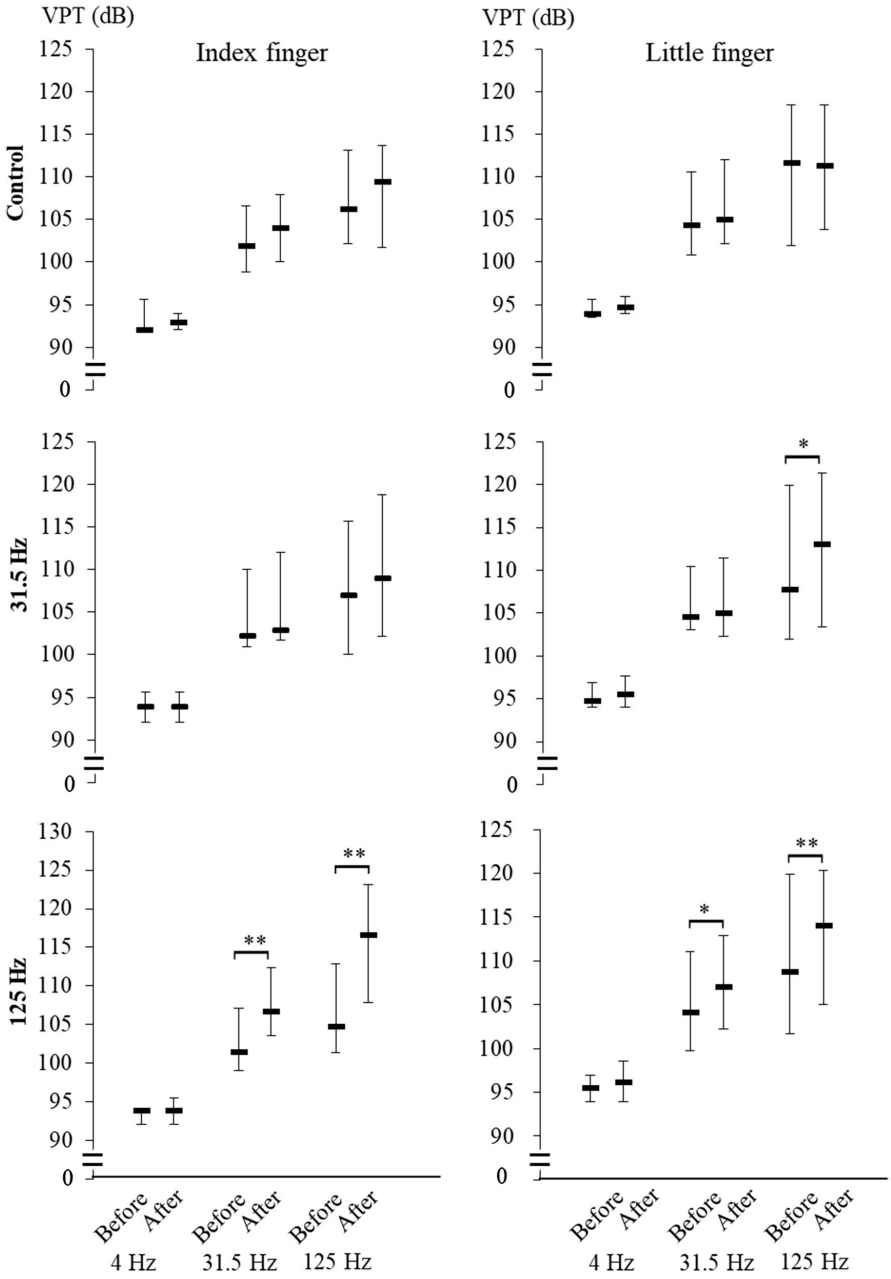

Fig. 2 VPT (dB) in the index (left panel) and little (right panel) fingers at three different test frequencies under three exposure conditions. Values are presented as median and IQR (shown as error bars) for ten subjects. Significantly different from the corresponding before-exposure values: *P < .05 and **P < .01.

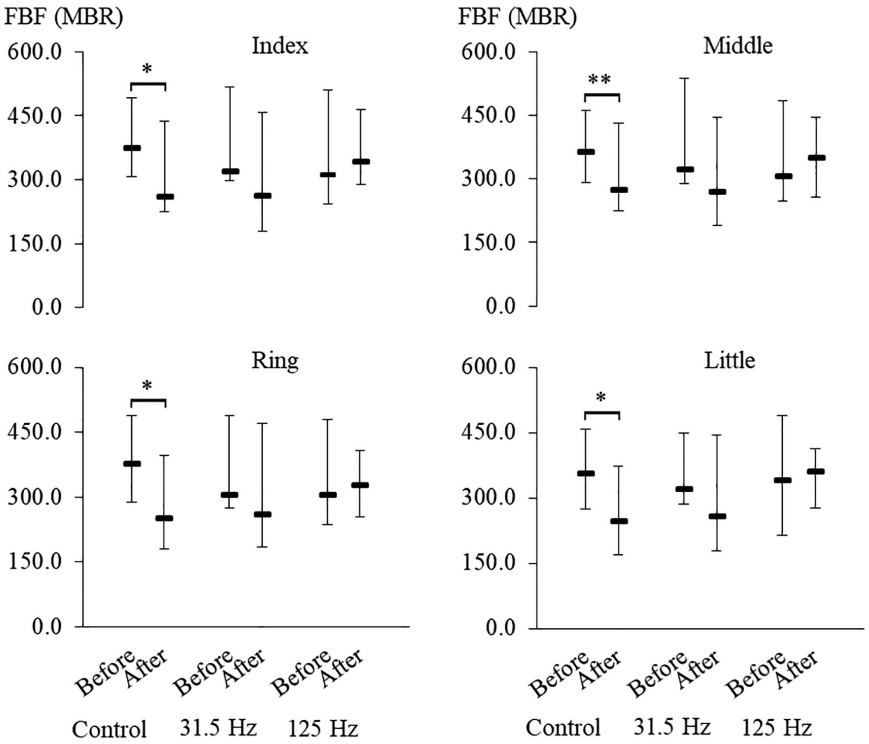

Fig. 3 FBF (MBR) in the index, middle, ring and little fingers obtained under three exposure conditions. Values are presented as median and IQR (shown as error bars) for ten subjects. Significantly different from the corresponding before-exposure values: *P < .05 and **P < .01.

latter period at all fingers (before exposure: median 356.4 to 379.2 MBR, IQR 171.3 to 201.1 MBR; after exposure: median 246.8 to 274.6 MBR, IQR 203.8 to 212.0 MBR) under the control condition (P < .05 to .01; Wilcoxon signed-ranks test). In contrast, compared to the corresponding before-exposure values, such a significant decrease disappeared after exposure under both 31.5 Hz and 125 Hz exposure conditions (P > .05). Furthermore, although not significant, FBF after exposure was higher than the corresponding baseline values at all fingers under 125 Hz exposure condition (before exposure: median 307.0 to 342.1 MBR, IQR 238.7 to 277.1 MBR; after exposure: median 328.9 to 360.9 MBR, IQR 136.6 to 187.7 MBR).

Discussion

Vibrotactile perception in fingers are thought to be mediated by four types of skin mechanoreceptors: slowly adapting I (SAI; Merkel discs), slowly adapting II (SAII; Ruffini endings), fast adapting I (FAI; Meissner corpuscles) and fast adapting II (FAII; Pacinian corpuscles).[15] It has been postulated that activation of such skin mechanoreceptors also causes central sympathetic reflexes which in turn leads to the changes in finger circulation.[3,4,16]

Among the above-mentioned four mechanoreceptors, SAII mechanoreceptors are considered to be not useful for detecting frequency responses in the hands, and therefore, the international standard ISO 13091-1 (2001) recommended obtaining VPT at the fingertips, mediated separately by SAI, FAI and FAII mechanoreceptor populations by providing stimulation at a minimum of 4 Hz, 31.5 Hz and 125 Hz, respectively.[14] In this study, we also measured the VPT at these minimum three test frequencies before and after exposure of subjects to HAV of 31.5 Hz and 125 Hz with the same frequency-weighted acceleration 5.5 m/s^2 rms.

In this study, compared to the control condition, exposure to a certain frequency of vibration was expected to cause greater changes in VPT relevant to that particular mechanoreceptor.[10] According to our hypothesis, vibration exposure at the frequencies of 31.5 Hz and 125 Hz were expected to show the greater changes in VPT at 31.5 Hz and 125 Hz test frequencies, respectively, by causing changes in vibrotactile sensitivity of the corresponding mechanoreceptors. However, as revealed under the 125 Hz exposure condition, vibrotactile sensitivity showed significant changes at both 31.5 Hz and 125 Hz test frequencies in both fingers. In other words, at 125 Hz exposure condition, vibrotactile sensitivity not only of the Pacinian corpuscles, but also of the Meissner corpuscles was affected. This might have been caused by the fact that at a relatively high magnitude of vibration exceeding the threshold applicable for a particular mechanoreceptor, other mechanoreceptors become involved in the responses in vibrotactile perception.[17,18] Our findings are in line with those of Burström et al., who also exposed subjects to vibration of 31.5 Hz and 125 Hz frequencies with two same frequency-weighted accelerations (2.5 or 5.0 m/s^2 rms), and showed that the acute changes in vibrotactile thresholds were significant for the vibration stimuli of 125 Hz only.[6]

In our study, significant reductions in FBF were observed from a push force of 2 N under the control condition in all fingers. The findings are in line with the findings of Bovenzi et al. who also revealed such significant decrease in FBF after exposure of the middle finger to the same push force (2 N).[4] In contrast, compared to the corresponding before-exposure values, exposure to acute vibration prevented such significant reductions in FBF under both 31.5 Hz and 125 Hz exposure conditions, and led to an increasing trend in FBF (although not significant) under the latter exposure condition. We assumed that exposure to vibration of a particular frequency causing greater changes in VPT (as observed earlier, 125 Hz) should also cause greater changes in FBF at that vibration exposure frequency. Considering the changes under the control condition and compared to the corresponding before-exposure values, opposite pattern of responses in FBF were observed under the 125 Hz exposure condition as a result of exposure to acute vibration, which corresponds to the observed greater changes in VPT at that exposure frequency. From the above-mentioned findings, it can be postulated that Pacinian mechanoreceptors probably played a predominant role in causing vibration-induced changes in FBF induced by acute exposure to vibration of 31.5 Hz and 125 Hz, but with the same magnitude of vibration (5.5 m/s^2 rms). Our findings of greater changes in FBF observed under 125 Hz exposure condition are consistent with those of previously published studies. In a study by Bovenzi et al., the investigators exposed healthy subjects to vibration ranging between 16 to 125 Hz frequencies with a frequency-weighted acceleration of 5.5 m/s^2 rms under all conditions and observed that the higher was the frequency of vibration, the stronger was the change in FBF after exposure.[5] Also, a number of other previous experimental investigations with acute exposure of subjects to HAV of same frequency-weighted acceleration using different frequencies ranging between 16 to 1000 Hz revealed more significant changes in finger circulation of the exposed and/or unexposed hands at exposure frequencies higher than 30 Hz compared with the frequencies lower than the latter.[5,7,9] However, the studies mentioned above reported vasoconstriction from exposure to vibration, whereas in the current study, we observed inhibition of vasoconstriction from such exposure. A number of prior studies also reported similar response patterns in FBF to acute vibration at the dorsal side of fingers.[11,19] In the latter studies, the authors postulated that a reduction in the release of endothelin from smooth muscle into the vessel cavity during vibration and vibration-induced increase in the activity of vasodilator system on the dorsal side of fingers might be responsible for such observed responses in FBF. However, this topic warrants future research as controlled short-term exposure to HAV seems to have the potential to induce improvements in peripheral circulation and may possibly contribute to the treatment of diseases with vascular spasms.

To assess the frequency-dependence of the

physiological or biodynamic responses of human fingers to HAV, the frequency weighting W_h has been recommended by the international standard ISO 5349-1 (2001), which is based on the frequency-weighted vibration acceleration applicable for various frequencies.[12] According to this standard, vibration of the same magnitude (i.e. frequency-weighted acceleration) should cause same physiological responses in human fingers irrespective of the vibration exposure frequencies. In this study, we observed that acute exposure of subjects to vibration of two different frequencies but with the same frequency-weighted acceleration did not produce changes in VPT to the same extent. Also, at those two exposure frequencies with the same frequency-weighted acceleration, the changes in FBF showed somewhat different patterns of responses. A number of published studies concluded that the frequency weighting W_h as specified in ISO 5349-1 does not appear to reflect the frequency-dependence of the physiological or biodynamic responses of human fingers to hand-arm vibration.[5,20,21] Our above-mentioned findings also support the growing body of literature suggesting that the international standard ISO 5349-1 (2001) is not suitable for assessment of the acute changes in vibrotactile perception and finger circulation induced by exposure to HAV.[6,20,22]

However, the findings of this study should be interpreted in light of several possible limitations. First, the subjects were exposed to vibration generated at two frequencies only. However, these are two most common frequencies in the literature used for the purpose. Second, there may be a question of measurement bias for FBF due to the movement of the exposure hand. However, we believe that such an effect on FBF caused by hand movement should be limited as the movement was passive (performed by the experimenter) and a control condition was used in this study. Also, such a passive movement of the exposed hand for measurement of FBF during recovery period has been reported in the literature.[22] Third, in this study, we observed an increasing trend in FBF under 125 Hz exposure condition which did not reach the required level for statistical significance. This might have been caused by the facts that the number of subjects included in this study was small and the statistical power was also not enough for observation of such effects.

Conclusions

In this study, we revealed that from exposure of healthy subjects to HAV of 31.5 Hz and 125 Hz exposure frequencies with a magnitude of 5.5 m/s^2 rms, the responses in VPT were probably predominantly mediated by the Pacinian mechanoreceptors. Furthermore, the slightly different response patterns in FBF under those two vibration exposure frequencies with greater changes under the 125 Hz exposure condition suggest the possibility of a greater role of the Pacinian mechanoreceptors in regulation of finger circulation at the magnitude of vibration used in this study. Our results also suggest that acute exposure to short-duration HAV can prevent vasoconstriction resulting from the push force exerted by the exposed fingers. However, these issues need to be investigated further and confirmed in future studies with exposure of subjects to different frequencies (both higher and lower) of HAV involving different skin mechanoreceptors mediating those vibrations.

Acknowledgments

This research was supported by a Grant-in-Aid for Scientific Research (no. 26460803) from the Japan Society for Promotion of Science (JSPS).

Conflict of Interest

The authors declare no conflict of interest.

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