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Effect of vibration frequency on finger blood flow

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Summary. A total of 18 healthy subjects (9 men and 9 women) 20–35 years of age were used to study the effect of vibration frequency on finger blood flow. Seven vibration frequencies of 16, 31.5, 63, 125, 250, 500 and 1,000 Hz, at vibrational accelerations of 10 m/s^2 (rms: root mean square) or 50 m/s^2 (rms), with the exception of 16 Hz, which was measured at only 10 m/s^2 (rms), were randomly applied to the palm of the right hand for 1 min at intervals of about 3 min. Finger blood flow was measured simultaneously in both the right and the left middle fingers with a blood flowmeter using a thermal diffusion method and in the left middle finger with a laser Doppler flowmeter. The experiments were performed in an artificial climate chamber set at 23°C air temperature and 50% humidity. Relatively great responses were observed at frequencies of 31.5–63 and 250–500 Hz on the exposed and unexposed sides, respectively, as measured with a blood flowmeter using a thermal diffusion method and at 31.5–63 as well as 500 Hz on the unexposed side with a laser Doppler flowmeter. These results may be related to Meissner's and pacinian corpuscles.

Key words: Vibration – Frequency – Finger blood flow – Thermal diffusion method – Laser Doppler flowmeter

Introduction

It is important to know which vibration frequency is the most hazardous from the standpoint of preventing vibration syndrome. Several experimental studies on the effects of vibration frequency on peripheral circulation have been carried out in humans: Pyykkö and Hyvärinen (1973) and Färkkilä and Pyykkö (1979) used plethysmography, Nasu (1977) used thermography, and a recent study by Nohara et al. (1986) applied a hydrogen gas-clearance method to measure blood flow. However, the findings are not consistent as to the vibration frequency causing the most prominent response.

In the present study, to evaluate one of the physiological effects of vibration frequency, we observed changes in finger blood flow induced by vibratory stimulus and investigated the effects of vibration using two non-invasive skin-blood flowmeters. One device was a flowmeter using the thermal diffusion method developed by Brawley (1968) and Carter et al. (1973), which was adapted by Nakamura (1987) for the measurement of body surface circulation, and the other was a laser Doppler blood flowmeter developed by Stern (1975), which has recently been improved.

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Subjects and methods

A total of 18 subjects, including 9 healthy men and 9 healthy women aged 20–35 years, were examined in the present study. Subjects were seated with their right palm placed downward on the vibrating plate. The left hand was positioned palm downward on a table at the same height as the right hand. Ear plugs were used to minimize the noise of the vibration load and to maintain quiet. Seven vibration frequencies of 16, 31.5, 63, 125, 250, 500 and 1,000 Hz were used at vibrational accelerations of 10 m/s^2 (rms: root mean square) or 50 m/s^2 (rms), with the exception of 16 Hz, which was measured at only 10 m/s^2 (rms), for a total of 13 settings. The order of the 13 vibration exposures was determined for every subject by a table of random numbers. In each vibration exposure, the right palm was exposed for 1 min at intervals of about 3 min. During this period the values on each blood flowmeter were continuously recorded by a three-channel recorder (Graphtech, SR-6335). The vibration was generated by a compact vibration generator (Riken Onkyo, RV-01) in combination with an oscillator (NF Electronic Instruments, E-1001A) and a power amplifier (Emic, 374-A). A vibration accelerometer (Rion, VM-50) was used to measure the acceleration levels so as to identify elevated peak vibrations and to ensure a constant acceleration level during the experiments.

Finger blood flow was measured using a blood flowmeter based on the thermal diffusion method (Biomedical Science, TGA-2), whereby sensors were attached to the back of the middle phalanx of the third fingers of both hands. Simultaneous recordings of the left hand were obtained with a laser Doppler blood flowmeter (Biomedical Science, LFA-2) attached to the palm side of the third left finger. For evaluations of blood flow values in both hands by the thermal diffusion method, the mean value for 1 min before exposure to each vibration (the initial value) and the mean value for 1 min during vibration exposure (the exposed value) were measured, and the rate of change was calculated. For measurements by laser Doppler flowmeter, the blood flow value just before vibration exposure was designated the initial value, which was compared with the value measured during vibration exposure. In evaluations carried out by laser Doppler flowmeter, the percentage of subjects exhibiting blood flow reductions of 50% following each vibration was determined. All experiments were performed in early November of 1989 in an artificial climate chamber set at 23°C air temperature and 50% humidity.

Results

Figure 1 shows part of the measurement values recorded for a 21-year-old man. The blood flow in the finger of the right hand (exposed side) showed a pattern of reduction immediately after the vibration started, with an increase occurring after the vibration had been terminated. The finger of the left hand (unexposed side) exhibited a change in blood flow similar to that measured on the exposed side. Values simultaneously recorded using the laser Doppler blood flowmeter on the unexposed sides showed a slight difference in movement, but the general trends were in agreement.

The mean rate of change in blood flow for 1 min during vibration exposure against the initial value was calculated for 18 subjects and the results are shown in graph form (Figs. 2, 3). Figure 2 shows the mean rate of change (mean ± SEM) for the exposed side during vibration. Significant reductions in blood flow were observed except at frequencies of 125 and 1,000 Hz at 10 m/s^2 and 125 Hz at 50 m/s^2. Relatively great responses were observed at frequencies of 31.5–63 and 250–500 Hz on the exposed sides. The same trend was observed on the unexposed side, as shown in Fig. 3, although to a lesser degree than on the exposed side.

Figure 4 shows the results obtained using a laser Doppler flowmeter on the unexposed sides. The percentage of subjects exhibiting blood flow reductions of ≥ 50% following each vibration is indicated. As in Fig. 3, most reactions were recorded in the vicinity of 31.5, 63 and 500 Hz.

Discussion

In the present study, we found that the more pronounced reduction in finger blood flow on both the exposed and the unexposed sides occurred at frequencies of 31.5–63 and 250–500 Hz. Some previous vibrational load studies using human subjects have reported the effects of vibration frequency on peripheral circulation. Pyykkö and Hyvärinen (1973) studied vasoconstriction reaction on the exposed side at various vibration frequencies using plethysmography and reported that the strongest effect occurred at 125 Hz. Färkkilä and Pyykkö (1979) used plethysmography to study vascular reaction in the right

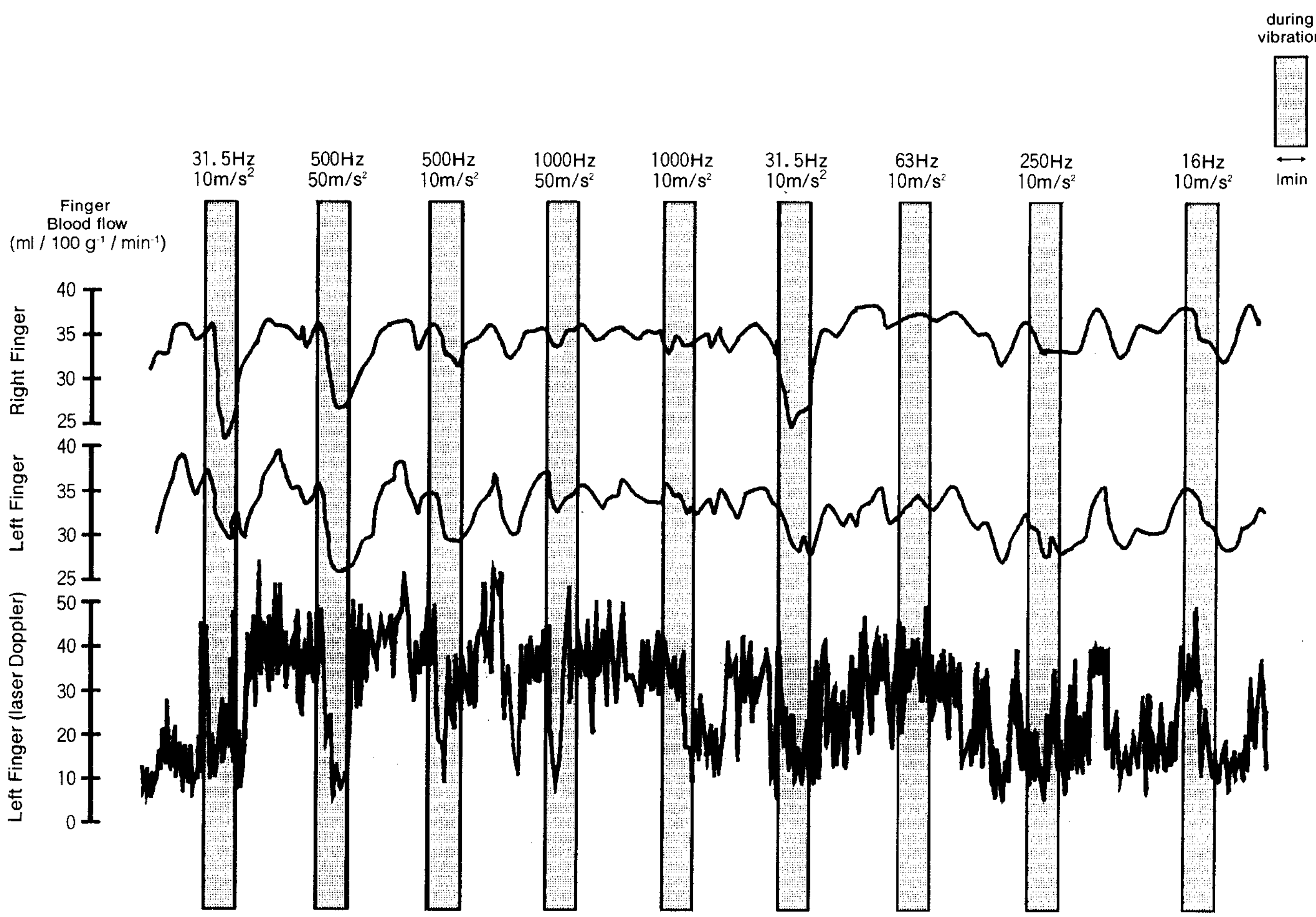

Fig. 1. Example of blood flow recordings for one subject (21-year-old man) during vibration exposure and rest periods. The *upper line* and the *middle line* represent blood flow fluctuations as determined by flowmeter using a thermal diffusion method in the right (vibration-exposed side) and the left (unexposed side) third fingers, respectively. The *lower line* represents blood flow fluctuations as determined using a laser Doppler blood flowmeter in the left third finger

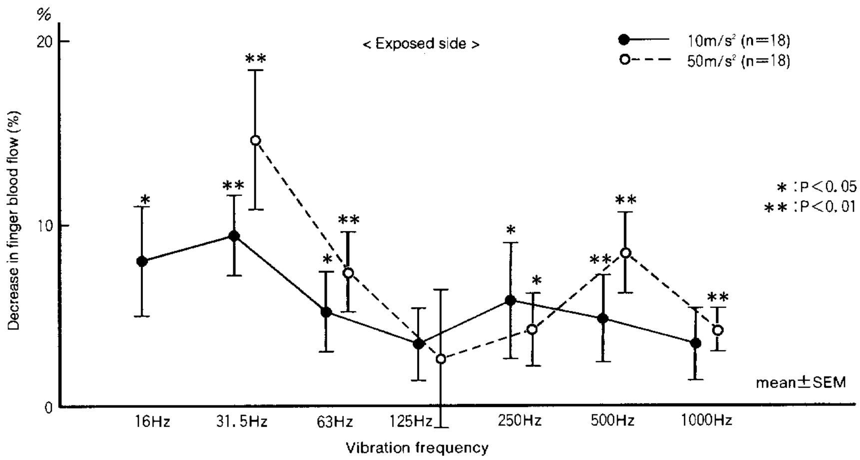

Fig. 2. The mean rate of change (mean ± SEM) in blood flow for 1 min during vibration against the initial value (the value for 1 min before the start of each vibration exposure) in the right finger (exposed side). *Asterisks* indicate statistical significance at the 5% level and *double asterisks* indicate statistical significance at the 1% level, based on the null hypothesis that the rate of decrease is equal to 0

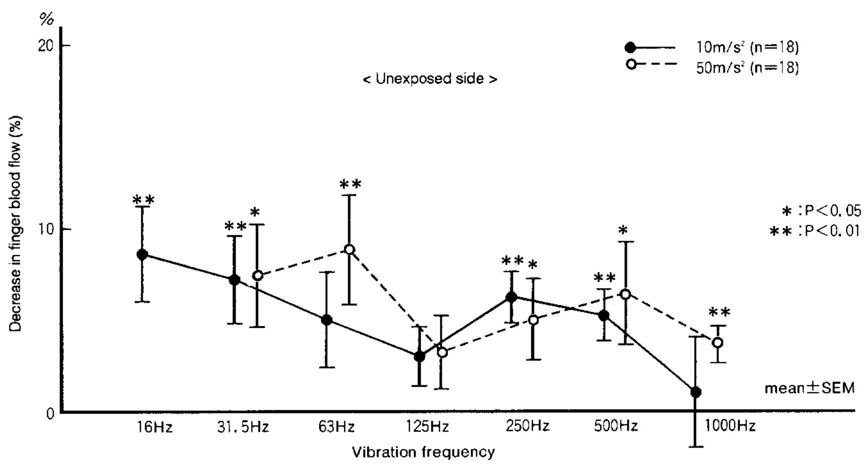

Fig. 3. The mean rate of change (mean ± SEM) in blood flow for 1 min during vibration against the initial value (the value for 1 min before the start of each vibration exposure) in the left finger (unexposed side). *Asterisks* indicate statistical significance at the 5% level and *double asterisks* indicate statistical significance at the 1% level, based on the null hypothesis that the rate of decrease is equal to 0

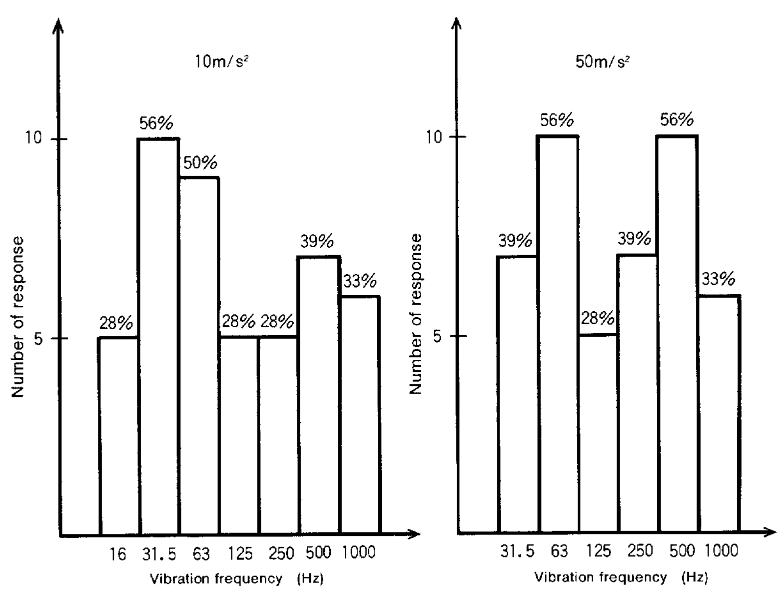

Fig. 4. The number and the percentage of subjects ($n = 18$) exhibiting blood flow reductions of ≥50% following each vibration in the left finger (unexposed side) as determined using a laser Doppler flowmeter

hand (unexposed side) when vibrational exposure was applied to the left hand and reported that vasconstriction reactions occurred most frequently at 60 Hz, whereas the greatest amplitude occurred at 200 Hz.

Other studies investigating peripheral circulation on the unexposed side include a study by Nasu (1977) using thermography. Nasu observed reductions in skin temperature on the unexposed side during 3-min exposure periods at frequencies of 40, 80, 100 and 120 Hz (constant amplitude) and reported that the most pronounced reduction occurred at 100 Hz. However, Harada (1978) carried out vibration load tests using 5-min exposure periods at eight frequency levels between 8 and 1,000 Hz in a detailed study of change in skin temperature and vibration sensation threshold at the fingertips and reported that statistically significant reductions in skin temperature occurred at 250 Hz on both the exposed and the unexposed sides at 6 min after exposure. He also observed decreasing skin temperature trends at 16 and 31.5 Hz.

Examples of other studies directly measuring finger blood flow include that of Nohara et al. (1986) using a hydrogen gas-clearance method. In this study, vibration at six frequency levels between 30 and 960 Hz (constant acceleration) was applied over 60 min and compared with blood flow measurements obtained before and after exposure to vibration. This is by far the longest exposure period yet reported, and significant blood flow reductions on the exposed side were reported at 60 and 480 Hz.

Although these studies used a variety of different methods to evaluate load conditions and peripheral circulation, which makes comparisons difficult, they can be broadly divided into two groups: reports of serious reactions in the vicinity of 100–125 Hz and reports of two peak reactions at around 30–60 Hz and 250–500 Hz. The reports by Pyykkö and Hyvärinen (1973) and Nasu (1977), which support the former findings, are invariably based on amplitude (displacement), and we must be aware of differences in conditions and loads at constant acceleration. If displacement is constant, the effect on the low-frequency side can be ignored because acceleration is proportional to the frequency squared. In the latter studies, vibration at almost constant acceleration were applied, except in Harada's study (1978). Although load conditions were set at three constant velocity levels in the latter study, two peaks in skin temperature reduction were observed in the low-frequency (15–31.5 Hz) and high-frequency (near 250 Hz) ranges, even when viewed at the constant acceleration. In the previous studies, therefore, vibration frequency effects on finger blood flow under conditions of constant acceleration can be said to support the findings of our investigation.

In the above-mentioned studies, exposure times were about 3 or 5 min, except in the study by Nohara et al. (1986). Our 1-min exposure time was shorter than those in previous studies because, using the two recently developed flowmeters, the reactions in blood flow were observed immediately after the start of vibration and were a priority in the present study. It is interesting that our results almost agreed with some findings of previous studies, although there were differences in vibration exposure time.

Our findings disclosed nearly parallel reactions in the blood flow of both the exposed and the unexposed sides and a pronounced reduction in blood flow at similar frequencies on both sides. Burton (1939) reported that plethysmography wave forms recorded virtually parallel changes in the fingers of the right and left hands, and Bini et al. (1980) reported that the skin-nerve sympathetic activity of the hands showed similar vasoconstrictor bursts of the right and left median nerves and a positive correlation in their amplitudes. Kondo et al. (1987) found a strong correlation between the vibration-exposed finger and the unexposed finger in the amount of skin temperature reduction caused by vibration exposure. The reason why the finger blood flow in both hands can be changed simultaneously is believed to involve the sympathetic reflex, as suggested in some previous studies.

Hyvärinen et al. (1973) suggested the possibility that pacinian corpuscles are the vibratory stimulation receptor causing the vasoconstrictive reaction. Pacinian corpuscles are sensitive to frequencies of ≥ 60 Hz and their known optimal frequency is near 200 Hz (Sato 1961; Mountcastle et al. 1967; Talbot et al. 1968). However, Mountcastle et al. (1967) reported clear evidence of a "cutaneous movement detector" (i.e., Meissner's corpuscle) other than the pacinian corpuscle at vibration frequencies of < 60 Hz and found that its optimal frequency was 30–40 Hz. The present findings of marked reductions in the finger blood flow on both sides at frequency ranges of 31.5–63 and 250–500 Hz may be related to both Meissner's and pacinian corpuscles.

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