ORIGINAL ARTICLES

Effect of Exposure to Hand-Transmitted Vibration on Digital Skin Temperature Change

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Abstract: Right palms of 10 healthy subjects were exposed to vibration of 5 minutes' duration and a series of skin temperature changes was measured from both middle fingers and both great toes, with a view to clarifying the remote effect of hand-transmitted vibration on vasoconstrictor tone in exposed and unexposed digits. While the skin temperature changes varied widely from subject to subject, significant skin temperature decreases occurred in the presence of the vibratory load. In addition, a positive correlation of significance was demonstrated in skin temperature decrease between the vibration-exposed fingers and each of the other unexposed three digits. It was hence concluded that local vibratory application yielded vasoconstriction in the remote digits as well as in the neighbouring region, and it was considered that the somatosympathetic reflex mechanism probably contributed to this response.

Key words: Hand-transmitted vibration—Vibration syndrome—Skin temperature—Vasoconstriction

INTRODUCTION

As already generally observed, vibrating instrument operators occasionally experience various subjective complaints such as chills or numbness in their hands and arms, with which vibrating tools are usually held. They also develop similar symptoms in their lower limbs. In his clinical study, Takagi¹⁾ dealt with the issue of polyneuropathy observed in the lower limbs of chain-saw operators.

One of the coauthors, Sakakibara,²⁾ made an extensive survey in 1982 in which 1687 patients with diagnosed vibration syndrome replied to a self-administered questionnaire. Of these, the data from 325 chain-saw operators were subjected to multivariate analysis, since the rest of the patients were affected by heart disease, hypertension, diabetes mellitus, liver disease, and trauma. These underlying conditions would likely confound the analytical process. The results revealed that the frequency of vibration-induced white fingers tended to increase with accentuating degree of chills or numbness in the lower extremities besides those in the upper ones. His description suggested that it should be a matter of concern to evaluate the vibration-induced circulatory disturbance in the lower as well as the upper extremities. The aim of our study is to examine the effects of hand-transmitted vibration on the state of peripheral circulation in healthy men, with the main emphasis upon changes in digital skin temperature.

EXPERIMENTAL METHODS

Since the laboratory room temperature, the way of keeping subjects warm, and the posture of subjects seemed to relate closely to skin temperature changes, they were varied in several preliminary trials that preceded the present experiment with the cooperation of the same subjects.

As a consequence of these trials, the following facts were revealed.

- (1) The primary requirement was to prevent the skin temperature in the lower extremities from cooling down at rest.
- (2) Palmar temperatures should be prevented from radiating through the vibrator disk.
- (3) Consistent skin temperature between 35 and 36°C just prior to the experimental start provided the best reproducibility and sharpness in response to stimulation.

Based on these, the experimental conditions were designed as follows.

1. *Vibrator*

An electrodynamic vibrator with an air spring support (Akashi, ASE-12) employed in this study shows flatness in frequency characteristic from 5 to 9000 Hz, reaching its maximal acceleration level of 98 m/sec² with a load of 42 kg. An aluminum plate of 1.5 cm in thickness, 20 cm in diameter, and 1.2 kg in weight was bolted to the moving part of the vibrator and fixed with a Bakelite disk of the same diameter on it. For avoidance of heat radiation, the disk was covered with thin nylon.

2. *Vibration parameters*

A sinusoidal wave produced in this study was kept at an acceleration level

of 98 m/sec^2 (root mean square) with a frequency of 125 Hz, presumably appropriate to cause apparent physiological responses. To keep the acceleration level constant, an accelerometer (Rion, VM50) was attached to the disk for monitoring.

3. *Noise elimination method*

Earplugs were used for elimination of the influence of the vibrator generating noise [60–63 db(A)].

4. *Room temperature*

In an attempt to keep the room temperature fluctuation at minimum, this vacillation was eventually found to range as little as within 0.7°C in the course of measurement for the individual subject. Throughout the measurement for all subjects, the room temperature fluctuated from 22.8 to 24.4°C .

5. *Subjects*

The 10 subjects, aged from 21 to 32, were all in excellent health. The characteristics of their peripheral circulation were not unusual.

6. *Posture of subject*

The subjects sat in an armchair, extending their knees horizontally on a box. Then, these subjects were instructed to place their unfolded right palms lightly on the vibrating disk and to rest their left forearms on the arm of the chair. Each was dressed in indoor clothing, wore a pair of thin nylon socks, and was blanketed below the knees. The height of the chair was adjusted so that sitting subjects could hold out their right palms on the disk with their elbows lightly flexed.

7. *Method of skin temperature measurement*

Thermistor electrodes (Takara Kogyo) were attached on the dorsal surfaces of the distal phalangeal joints of both middle fingers and of the proximal phalangeal ones of both great toes. Thereafter, the skin temperatures of these four sites were measured simultaneously and recorded every 30 seconds with an automatic dotting register (Hokushin Denki), the sensitivity of which was known in advance to be $\pm 0.075^\circ\text{C}$. About 90 minutes passed from the time when the subjects entered until the measurement was completed.

8. *Date of experiment*

The preliminary trials were carried out to establish the experimental conditions from December 7 through December 29. In the light of these results, the main tests were conducted from November 11 through November 27 between 2 and 4 p.m.

The whole experimental procedure was accomplished as follows.

- (1) Subjects had been in the sitting posture as already mentioned for at least 30 minutes to obtain a skin temperature equilibrium between 35 and 36°C at the measurement site.
- (2) Subjects' palms were extended on the center of the non-vibrating Bakelite disk for 5 minutes in the reference tests.
- (3) Subjects maintained in the same sitting posture for more than 15 minutes after removing their palms from the disk.
- (4) The palms were again placed on the center of the vibrating Bakelite disk for 5 minutes in the load tests.

It was verified in the preliminary tests performed several times as above mentioned that the response observed in the initial tests gave the best sensitivity. For this reason, we conducted only one reference and one load test in a series of experiments for one subject.

RESULTS

1. *Change in skin temperature at each measurement site*

For convenience' sake, the point of time at which the subjects' palms were placed on the disk was tentatively referred to as "S" and that of removal from the disk as "E". "RF" and "LF" indicated the right middle finger and the left middle finger, respectively, while "RT" and "LT" represented the right great toe and the left great toe, respectively. The peripheral skin temperature of the digits was briefly termed the "skin temperature" unless otherwise specified.

Recording of skin temperatures at 30-second intervals began 3 minutes or more before S and ended over 5 minutes after E.

While the average value of the 3-minute skin temperatures measured before S was defined as the "initial value," the "skin temperature change" was calculated by subtracting the observed temperature from the initial value. The skin temperature changes during the 10 minutes, the former 5 minutes from S and the latter 5 from E, were obtained from such calculation (Fig. 1). As listed in Table 1, the means of the 10 subjects' initial values at each site differed little between the two tests.

Table 1. Initial skin temperature at four measurement sites

	Reference test	Load test
Right finger	35.50±0.06	35.42±0.09
Left finger	35.39±0.09	35.28±0.10
Right toe	35.65±0.12	35.80±0.11
Left toe	35.60±0.13	35.76±0.11

Values indicate the means±S.D. (°C) of 10 subjects.

Fig. 1. Curves of skin temperature changes during ten minutes in the reference tests (a) and in the load tests (b). The degree of skin temperature changes ($^{\circ}\text{C}$) is plotted along the ordinates, and the time elapsed (minute) after the palmar placement along the abscissas. Heavy lines represent the mean values of skin temperature changes. In the reference tests each subject's right palm was placed on the non-vibrating disk for five minutes ($\longleftrightarrow$), in the load tests on the vibrating disk for the same duration ($\longleftrightarrow$).

Figure 1 (a) shows the skin temperature changes of the 10 subjects and their mean values in the reference tests. At a glance the skin temperatures tended to fluctuate within a small amplitude with lapse of time, though a moderate amplitude increase of the changes came after the right palm removal from the disk. In one case, the LF, RT and LT skin temperature changes had transient peaks during the latter 5-minute period.

The skin temperature changes and their mean values in the load tests are shown in Figure 1 (b). As seen in this figure, the skin temperatures changed even more in the load tests than in the reference ones. Of the troughs of the RF skin temperature changes in the 10 subjects for 10 minutes, a value of -1.48°C was found to be the deepest; the corresponding figures for the LF, RT and LT changes were -1.55°C , -1.43°C and -1.35°C , respectively.

Table 2. Skin temperature changes at four measurement sites at different times after the palmar placement on the disk

Time after S (minute)	Right finger		Left finger	
	Reference test	Load test	Reference test	Load test
1	-0.02 ± 0.04	$-0.33 \pm 0.07^*$	-0.04 ± 0.02	$-0.23 \pm 0.07^*$
2	0.05 ± 0.07	$-0.30 \pm 0.13\text{NS}$	-0.01 ± 0.04	$-0.36 \pm 0.11\text{NS}$
3	0.11 ± 0.06	$-0.40 \pm 0.17^*$	0.00 ± 0.05	$-0.49 \pm 0.14^*$
4	0.13 ± 0.09	$-0.46 \pm 0.20^*$	-0.01 ± 0.04	$-0.49 \pm 0.18\text{NS}$
5 (E)	0.06 ± 0.06	$-0.42 \pm 0.16^*$	0.00 ± 0.04	$-0.48 \pm 0.17^*$
6	-0.02 ± 0.06	$-0.53 \pm 0.20\text{NS}$	-0.01 ± 0.07	$-0.55 \pm 0.16^*$
7	-0.04 ± 0.08	$-0.51 \pm 0.15^*$	-0.03 ± 0.12	$-0.63 \pm 0.16^*$
8	-0.04 ± 0.09	$-0.41 \pm 0.12\text{NS}$	-0.03 ± 0.11	$-0.55 \pm 0.13\text{NS}$
9	-0.07 ± 0.08	$-0.45 \pm 0.12^*$	-0.01 ± 0.08	$-0.54 \pm 0.13^*$
10	-0.05 ± 0.06	$-0.49 \pm 0.11^*$	-0.06 ± 0.04	$-0.59 \pm 0.12^*$

Time after S (minute)	Right toe		Left toe	
	Reference test	Load test	Reference test	Load test
1	0.01 ± 0.03	$-0.06 \pm 0.03\text{NS}$	0.03 ± 0.06	$-0.09 \pm 0.03\text{NS}$
2	0.05 ± 0.04	$-0.09 \pm 0.03\text{NS}$	0.08 ± 0.07	$-0.10 \pm 0.05\text{NS}$
3	0.07 ± 0.04	$-0.18 \pm 0.07^*$	0.11 ± 0.07	$-0.18 \pm 0.07^*$
4	0.06 ± 0.05	$-0.23 \pm 0.09^*$	0.13 ± 0.07	$-0.24 \pm 0.09^*$
5 (E)	0.10 ± 0.04	$-0.27 \pm 0.11^{**}$	0.15 ± 0.07	$-0.29 \pm 0.11^*$
6	0.15 ± 0.03	$-0.31 \pm 0.12^*$	0.18 ± 0.07	$-0.40 \pm 0.11^*$
7	0.23 ± 0.06	$-0.38 \pm 0.13^*$	0.21 ± 0.08	$-0.46 \pm 0.14^{**}$
8	0.25 ± 0.09	$-0.43 \pm 0.14^*$	0.25 ± 0.11	$-0.53 \pm 0.13^{**}$
9	0.26 ± 0.10	$-0.47 \pm 0.15^*$	0.22 ± 0.10	$-0.55 \pm 0.14^{**}$
10	0.21 ± 0.08	$-0.49 \pm 0.16^*$	0.19 ± 0.10	$-0.60 \pm 0.16^*$

Values indicate the means $\pm$ S.E. ($^{\circ}\text{C}$) of 10 subjects.

Asterisks (*) indicate statistical significance at 5% level and double asterisks (**) at 1% level.

NS=not significant

The mean value of the RF skin temperature changes decreased with time during the 5-minute vibratory stimulation, but afterwards this value changed little. The same trend was observed in the left fingers, except for a slight delay in leveling off. In the meantime, the curves obtained from both great toes gradually diverged during the 10-minute measurement period. These falling temperatures seemed no longer reversible even after load discontinuance.

The every-minute mean values of the skin temperature changes for the 10 subjects and their standard errors in the two tests are listed in Table 2. As shown in this table, the skin temperature reductions were all greater in the load tests than in the reference tests at every minute. For significance evaluation, the Wilcoxon matched-pairs signed-rank test was applied here, and the temperatures in the load tests were found to fall significantly at many of the measurement times. These results led us to consider that the vibratory load served to produce these significant skin temperature falls.

On the other hand, discernible individual variations of the skin temperature changes were seen in terms of amplitude of the 10-minute temperature fluctuations and trace pattern with lapse of time. To evaluate these differences in a quantitative way, we introduced a new concept of "marked responders" by arbitrarily calculating with the following procedures at three points, i.e., 150th second after S, E, and 150th second after E; first, we reckoned the mean values of the 10 subjects' skin temperature changes (M) and their standard deviation ($S.D.$) at these three points in the reference tests, and then regard those as marked responders whose corresponding skin temperatures in the load tests declined below the level of $M - 3 \times S.D.$ (Table 3).

In the RF observation the marked responders were 3 in number at the 150th second after S which increased to 4 at E, succeeded by the decrease to 2 at the 150th second after E. This meant that the marked response to the vibratory stimulation tended to fade gradually after the load cessation. A similar course was followed in the left fingers; at these three points the marked responders numbered 4, 5 and 2, respectively.

While only one marked responder was seen for the right toes and none for the left toes at the 150th second after S, the numbers reached 4 and 3 for the right and the left toes, respectively, at E. Unlike the observations of both middle fingers, no number reduction of these responders was seen for the right toes at

Table 3. Number of marked responders at the three points of time at four measurement sites in the load tests

	150th second after S	E	150th second after E
Right finger	3	4	2
Left finger	4	5	2
Right toe	1	4	4
Left toe	0	3	4

the 150th second after E, and they numbered more for the left toes at E. These results suggested that the post-stimulation skin temperatures of both great toes returned less rapidly and, in some cases, even demonstrated the later appearance of the effect as compared with the values of both middle fingers. While the great toes lagged behind the middle fingers in response appearance, we verified that these responses were systemic as far as the digital skin temperature was concerned. This will be further dealt with in the next section.

2. Relationship between right fingers and other digits in skin temperature change

As illustrated in Figure 1, the behavior of the skin temperature changes differed from subject to subject, responding to the vibratory stimulation.

Then we sought to evaluate the association of the remote effect on the skin temperature changes with the direct effect of the vibration entering the right palm. In Figure 2, two points of time, the 150th second after S (the midpoint of vibration) and E, were chosen for plotting the RF skin temperature changes

Fig. 2. Scatter diagrams of skin temperature changes in the right finger and those in other three digits at the 150th second after S (a) and at E (b).

Table 4. Coefficient of correlation in skin temperature changes between the right finger and the other three digits

	Left finger	Right toe	Left toe
150th second after S	0.932**	0.486	0.751**
E	0.839**	0.698*	0.600*

Asterisk (*) figures have statistical significance at 5% and double-asterisk (**) figures at 1% level.

against each of the LF, RT and LT changes. The correlation coefficient for each relationship is given in Table 4.

There was a significant positive correlation of the skin temperature changes between the right and the left fingers, both at the midpoint of vibration and at E. The correlation between the RF and the RT changes did not display the statistical significance at the midpoint. This was ascribed to the discrepancy of the skin temperature changes in one case, where the RT skin temperature fell less than expected at the midpoint in spite of the moderate RF skin temperature reduction. Closer association of significance was, however, attained at E. The relationship between the RF and the LT skin temperature changes was found close enough for significance.

DISCUSSION

Blood vessels play the role of regulating body temperature under nervous control. In particular, the tips of the fingers and toes are subject to this regulation in response to environmental stimulation such as heat and vibration, which is partly attributable to arteriovenous anastomosis development around these sites. Hence, use of these sites for skin temperature measurement in the present study is reasonable to evaluate the effect of vibration exposure.

In the beginning, we state the rationale for using skin temperature as an index of dermal blood flow. From Takagi's review,³⁾ the latter fairly governs the former in an appropriately draft-proofed chamber, for the fingers and toes consist of adipose tissue and bone without deep-seated muscle, so that changes in blood flow in these non-dermal tissues are nearly negligible. He affirmed that digital skin temperature change was a useful marker of digital blood flow change. Aschoff and Wever⁴⁾ stated that, though the relationship between the skin temperature and the dermal blood flow was generally qualitative, this association became so evident when observed in specific areas that relation curves could be obtained. In the present experiment, environmental factors were appropriately controlled for the subjects based on the results of the preparatory experiments concerning room temperature and heat insulation. This was evidenced by the stable results achieved in the reference tests. We came to an agreement here that the skin temperature reductions under the present testing

conditions reflected the vibration-induced vasoconstriction.

Another factor must be taken into account here. As pointed out by Sakurai,⁵⁾ the skin temperature reductions after vibration exposure depends greatly on gripping force. Our subjects were instructed to place their palms on the disk gently enough to avoid such influences.

In experiments by Hyvärinen and Pyykkö^{6,7)} with a plethysmograph, hand-transmitted vibration at a frequency of 125 Hz was the most potent in producing vasospasm on the exposed side, whereas a frequency of 60 and 100 Hz yielded the strongest effect on the unexposed side. Nasu⁸⁾ reported that a frequency of 100 Hz was the most efficient in causing skin temperature decreases on the non-vibrated side. Taking these previous evidences into account, we adopted a frequency of 125 Hz. Interestingly, 125 Hz is known to be the dominant frequency generated by the chain saw.

Appreciable skin temperature reductions yielded here in the accelerated side RF. A number of earlier works are relevant to this point. Sivertsson and Ljung⁹⁾ applied vibratory stimulation to isolated vascular smooth muscle preparations, and demonstrated an instantaneous reduction of the contractile force during the active phase. Azuma and Ohashi,¹⁰⁾ in a similar experiment, reported that such preparations were characterized by the following respects: changes in reactivity to noradrenaline, reductions of contractile force during vibration exposure, and a post-stimulation contraction enhancement occurring transiently. Though these evidences seem to be conflicting with ours, we should be aware that the vascular smooth muscles they prepared were isolated and denervated. Far from this, vascular smooth muscle in a living body receives the control of the autonomic nervous system.

The trigger-receptor in this mechanism is assumed to be the Pacinian corpuscle, which is ever known as the vibration detector. Furthermore, the muscle spindle receptor, which uniquely reacts to vibratory stimulation, is believed to play a certain role in this process. Therefore it was thought that occurrence of great skin temperature changes in the vibrated region resulted from combination of a localized reaction and a systemic neuro-reflux one.

In the present study, even the non-vibrated LF shared the exposure effect of the stimulation in producing a significant skin temperature reduction, i.e., vasoconstriction. Previous researchers have ever revealed the relationship between the vibration receiving hand and the non-receiving one with respect to skin temperature change and to vasotonia. Kimura *et al.*¹¹⁾ recorded a reduction of dorsal skin temperatures on the vibrated and non-vibrated hand. Nasu⁸⁾ also observed changes in skin temperature using a thermograph and visualized the temperature reduction of the dorsal-aspect of the unexposed side. Pyykkö and Hyvärinen⁷⁾ examined plethysmographic changes in pulse wave height during vibration exposure on a unilateral hand for healthy students and vibrating tool using workers with Raynaud's phenomenon. As a result of the tests, some subjects

showed significant pulse amplitude reductions, whereas their rate and degree were more apparent among the affected workers.

Heretofore, a small amount of literature has dealt with the effect of hand-transmitted vibration on foot and toe skin temperature. Asaba *et al.*¹²⁾ measured the dermal blood flow of vibration syndrome patients undergoing hot-spring bath therapy by means of ^{133}Xe and ^{85}Kr washout techniques and revealed that the sufferers had affected circulation in all four extremities as compared with a control group. Sakakibara²⁾ suggested that the chill sensation in the lower limbs was partly referable to such circulatory impairment. The observation of the significant RT and LT skin temperature reductions even in healthy subjects throws his suggestion into relief.

We should step into further discussion concerning the anatomical respect and the following references are relevant to this issue.

Pyykkö *et al.*⁷⁾ discussed the integrating role of the central nervous system, through which vibration received at the Pacinian corpuscle and vasoconstriction were linked to one another. Nasu, in the aforementioned article,⁸⁾ confirmed the whole-body effect of local vibration on the surface temperature. Miyamoto and Alanis¹³⁾ observed an impulse in the greater splanchnic nerve trunk generated by the limb-transmitted vibration in paralyzed cats and divided the recorded nerve responses into two types: the segmental and the non-segmental response. They also reported involvement of the supraspinal structures for generating the former and concluded that either the spinal cord or the higher center is associated with the sympathetic response. Our results indicate that, at the very least, the spinal cord participated in the sympathetic vasoconstriction of both the great toes and the non-vibrated fingers. To consider the integration of the central nervous system, we intend to pursue experimental studies on the effects of concomitant or alternative exposure to vibration, loud noise and cold provocation.

In addition to the digital skin temperature reductions of statistical significance, considerable individual variations were observed in these changes. The present load tests gave 4 or 5 marked responders and low-responding remainders.

While a tendency was noted, in the present study, for the skin temperature of the fingers to return to pre-test levels after termination of vibratory stimulation, a number of subjects exhibited continued temperature reductions in their toes. From a study by Pickering and Hess,¹⁴⁾ greater vasoconstrictor tone in the lower extremities was thought to be one of the major reasons for the trend toward less and later recovery.

We saw a significant correlation in skin temperature reduction between the regions exposed and unexposed to vibration. This meant that the degree of vasoconstriction of the unexposed fingers and toes was in proportion to that of the exposed fingers. Though the RF and the RT skin temperature reductions failed to fully correlate with each other at the midpoint of vibration, at E the relationship became closer. This occurred presumably due to the cumulative

effect on the fingers and toes during the stimulating periods. In this connection, the asymmetrical posture of the arms in this study did not permit a statistical comparison between the raw values of the RF and the LF temperatures because distribution of blood flow varies with posture.¹⁵⁾

Andreeva-Galanina¹⁶⁾ investigated vasotonia conditions in the fingers of vibration-exposed workers and classified these conditions into three types: constriction, unalteration, and dilation. The vasotonia differed from worker to worker and depended on the frequency band. She also found the greatest contractile-type response in the vicinity of 100 Hz.

The present outcomes corresponded to the earlier survey by Sakakibara²⁾ which revealed that circulation-related complaints in the lower extremities were associated with Raynaud's phenomenon occurring in fingers.

CONCLUSIONS

A previous questionnaire survey urged us to study the remote effects of local vibration on vasoconstriction. With application of vibratory stimulation on the right palms of 10 healthy subjects, we measured and analyzed digital skin temperature changes. The results obtained are summarized below:

- (1) Exposure of the right palms to vibratory stimulation yielded significant skin temperature decreases in the middle fingers on the same side; the hand-transmitted vibration also caused such reductions in unexposed left fingers and even in both great toes.
- (2) Evaluation of the association in skin temperature changes gave a significant positive correlation between the right middle fingers and each of the non-vibrated three digits.

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