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THE TEMPORARY THRESHOLD SHIFT OF VIBRATORY SENSATION INDUCED BY HAND–ARM VIBRATION COMPOSED OF FOUR ONE-THIRD OCTAVE BAND VIBRATIONS

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The aim of the present study was to define the multiple effect hand–arm vibration composed of four equally effective one-third octave band vibrations (63 Hz, 125 Hz, 250 Hz and 500 Hz) on the temporary threshold shift in vibratory sensation.

Seven healthy subjects were exposed to vibration by grasping a vibrated handle in a soundproof thermo-regulated room. The vibratory sensation threshold at 125 Hz was measured before and after vibration exposure at an exposed fingertip. At first we determined each acceleration of the component one-third octave band vibrations for each subject. These should induce the same magnitude of temporary threshold shift in vibratory sensation immediately after the vibration exposure ($\mathrm{TTS}_{v,0}$ as induced by the reference one-third octave band vibration (250 Hz, 4**g**). We measured $\mathrm{TTS}_{v,t}$ for the exposures of the composed vibrations and the four component vibrations. $\mathrm{TTS}_{v,0}$ was determined for each exposure according to the exponential recovery model stated in the previous study.

The $\mathrm{TTS}_{v,0}$ induced by the composite vibration was not longer than that which might have been induced by each component vibration. This result confirms our previous speculation that the component of the vibration inducing the largest $\mathrm{TTS}_{v,0}$ determines $\mathrm{TTS}_{v,0}$ by broadband random vibration.

1. INTRODUCTION

The known pathological effects of hand-transmitted vibration include peripheral circulatory and sensorineural disorders and deformation of bones and joints [1]. These effects depend on the intensity and frequency spectrum of vibratory exposure. Measurements of vibratory sensation have been useful in investigating hypoesthesia in vibratory tool operators and evaluating the acute effects caused by vibration exposure. Current methods of rating the effects of vibration employ equal sensation contours of vibratory stimulation, annoyance, threshold of vibratory sensation, tolerance limit and epidemiological analysis of vibration syndrome. As Griffin [2] has described, the current standards are a compromise based on considerable extrapolation and do not take into account all of the factors contributing to injuries. However, the psychological measurements as direct indices of the pathological effects of vibration are problematic at best. Doubts particularly arise as to the form and extent of the frequency weighting, the nature of the time dependency, the relative importance of different axes of vibration, and the influence of grip force and posture.

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A preceding study [3] proved that a new, self-recording vibratory sensation meter accurately measured temporary threshold shifts of vibratory sensation (TTS_V) on a fingertip after exposure to hand-transmitted vibration [3]. Regression analysis estimated the temporary threshold shift immediately after each vibratory exposure ($TTS_{v,0}$). At the same time, the analysis also estimated the time constant (t_c) or half-life time of TTS_V. The fit of the exponential function was very good for each exposure. These parameters enable us to examine more generally the relationship of TTS_V to the characters of vibration exposure, the subject and other factors. The estimated $TTS_{v,0}$ and t_c were used to examine the dependency of TTS_V on the characteristics of the vibration exposure and the subject. The $TTS_{v,0}$ of each subject proportionally increased with the power function of acceleration. This result enables us to predict $TTS_{v,0}$ at an arbitrary level of acceleration.

These results are useful in experiments to evaluate systematically the effect of broadband vibration exposure on TTS_V. In this paper, we focus on examining experimentally the most effective vibration composed of four one-third octave bands on TTS_V and discuss the multiplicative or additive effects of the composite vibration.

Maeda and Kume [4] investigated 16 kinds of vibration at the same overall level and measured TTS_V using the same vibratory sensation meter as Harada [5, 6] and Nishiyama and Watanabe [7]. TTS_V increased with the spread of the band through a low-pass or high-pass filter, until the cut frequency of the band crossed over 125 Hz. Maeda estimated TTS_V after exposure to a linear spectrum vibration; that is, a broadband vibration the acceleration level of which was proportional to the logarithmic frequency with a slope of less than 6 dB per octave. The result was that 89·64 Hz had the maximum effect on TTS_V with a vibratory sensation test frequency of 125 Hz. However, Harada and Griffin [6, 8] and Nishiyama and Watanabe [7] reported that octave bands with central frequencies of 125 Hz or 250 Hz involve the frequency maximizing TTS_V. The TTS_V decreases considerably as the exposed frequency recedes from 125–250 Hz. This means that Maeda and Kume [4] used exposure to a vibration composed of several octave bands that might cause quite different magnitudes of TTS_V. Thus it is difficult to determine TTS_V after exposure to a broadband vibration that is different from the linear spectrum vibration stated above.

In a preceding study [10], the composite vibration exposure consisted of two components that might induce equal volumes of $TTS_{v,0}$. These accelerations usually differed due to the individual differences in the relationship between $TTS_{v,0}$ and the acceleration of the vibration exposure. The result did not show a significant increase in $TTS_{v,0}$ compared to that of the component vibration exposures. Furthermore, the two vibrations (which should maximize the overall level of acceleration and induce the same $TTS_{v,0}$) did not show a significant increase of $TTS_{v,0}$ in that combination. These results suggest that the $TTS_{v,0}$ induced by broadband vibration exposure may be equal to the maximum $TTS_{v,0}$ induced by exposure to component vibrations with a narrow band. There may be no multiplicative or additive effect on $TTS_{v,0}$ due to the composite vibration. It was concluded that the component vibration inducing the largest $TTS_{v,0}$ determines $TTS_{v,0}$ by a broad-band random vibration.

We discussed the possibility that the accuracy and precision of the measurements were insufficient to detect any increment in the vibratory sensation threshold. Subjective variables, which usually accompany psycho-physical measurement, are major factors of error. Such variance or error could not be avoided, even though subjects well trained in the measurement of vibratory sensation threshold were used. A composite vibration above one-third octave bands and the participation of more subjects may confirm the validity of the result.

The composite vibration with a spectrum covering the most effective bandwidth on $TTS_{v,0}$ on the basis of our previous experiment [3, 7] and other studies [2], was thought to induce a much larger $TTS_{v,0}$ than by the component band vibration. If the magnitude of the acceleration of each component vibration is set to induce the same $TTS_{v,0}$, it is easy to examine whether both $TTS_{v,0}$ values induced by the composite and component band vibrations are equivalent. Therefore, in the present study we examine the effect of the composite vibration involving more components of one-third octave bands than used in the preceding study [10].

2. SUBJECTS AND METHOD

Seven healthy male students, aged 21–29 years (mean 22·0 years) with normal vibratory sensations (less than or equal to 5·0 dB at 125 Hz, 0 dB = 1 μm^{p-p} participated in this study. The experiment was carried out in a soundproof chamber maintained at 22°C.

Each subject was seated and, after becoming adapted to the chamber climate, exposed his left hand to vibration by grasping a metallic handle attached to an electro-dynamic vibrator (IMV, Japan). An electric heater warmed the handle to 32°C in order to prevent the hand from cooling. The subject kept a grip on the handle with 40 N grasping power and 0 N push–pull power during a 2 min exposure to vertical vibration, according to the basicentric co-ordinate system for the horizontally gripped handle. Results from previous studies [3, 7] suggested 40 N and 2 min as sufficient to induce TTS_V for this study. The exposures began only after the subject had shown a stable vibratory sensation threshold and skin temperature at the fingertips of 30°C for 15 min or more.

The vibratory sensation threshold was measured using the self-recording vibratory sensation meter developed in a previous study [3]. The measurement proceeded under a test frequency of 125 Hz, with a contact pressure of the fingertip at 1 N, and the velocity of vibratory level change at 1·25 dB/s. The stimulating vibration at first decreases from a certain level to induce the vibratory sensation. As long as the subject detects vibration, he keeps depressing the button switch in his right hand. As soon as he can no longer detect vibration, he stops pressing the switch. The stimulating vibration then builds up again. As soon as the subject can detect vibration, he again presses the switch. The switch "on" corresponds to the descending threshold determination and the switch "off" to the ascending threshold determination. Each threshold determination is alternately repeated twice. The moment at which the subject activates the button switch defines the time of his threshold. Threshold measurements were taken several times after exposure: at 30 s intervals for the first 2 min following exposure, and of 1 min intervals for 5, 10 and 20 min. The skin temperature of some fingertips of both hands was measured simultaneously for reference. The vibratory sensation threshold prior to exposure for an individual was the mean of three measurements at 5 min intervals before exposure. The temporary threshold shift of vibratory sensation ($TTS_{v,t}$) was the difference between the vibration sensation threshold (in dB) measured just before and at t seconds after each exposure. In this experiment, the $TTS_{v,0}$ and t_c, were determined by regression analysis, with the goodness of fit of the exponential recovery model for each exposure as arrived at in the preceding study [3]. The $TTS_{v,t}$ values less than or equal to those 3 min after the exposure were used as long as they did not amount to less than or equal to 0 dB or to the phase of bounce of TTS_V; that is, a pause in the decrease or a gentle and transient increase of the vibratory sensation threshold.

In Table 1 are shown the four different one-third octave bands selected to induce the same $TTS_{v,0}$, which were composed on the basis of the preceding study [10]. The prediction of the $TTS_{v,0}$ was regulated so that the composite vibration might not result in a $TTS_{v,0}$ above 40 dB, the upper limit of our vibratory sensation meter (see Figure 1). In the same

TABLE 1

Experimental exposure condition by subject and the acquired $TTS_{v,0}$ (dB) and t_c(s) by regression analysis using the observed data

Subject	Trial	Central frequency	Acceleration (g)	Order	$TTS_{v,0}$(dB)	t_c(s)	r^2
A	1	63	6	2	13·9	220	0·926
		125	4	1	16·1	236	0·907
		250	4	4	17·6	218	0·971
		500	5	5	18·2	134	0·991
		Composite	9	3	19·0	186	0·982
	2	63	6	1	19·5	71	1·000
		125	4	5	16·9	94	0·979
		250	4	4	17·6	150	0·984
		500	5	2	20·1	96	0·992
		Composite	9	3	20·5	101	0·972
	3	63	6	3	21·4	64	0·987
		125	4	2	22·5	66	0·995
		250	4	5	19·5	135	0·978
		500	5	1	21·8	108	0·995
		Composite	9	4	17·9	169	0·993
B	1	63	6	4	22·0	30	0·982
		125	4	3	18·7	58	0·979
		250	4	1	19·1	145	0·986
		500	6	2	25·2	59	1·000
		Composite	10	5	25·8	98	0·995
	2	63	6	2	9·7	74	0·984
		125	4	4	18·2	92	0·972
		250	4	5	18·5	93	0·994
		500	6	1	19·1	73	0·997
		Composite	10	3	18·8	93	0·993
	3	63	6	1	21·8	63	0·997
		125	4	4	16·7	136	0·968
		250	4	2	21·5	80	0·996
		500	5	3	22·7	84	0·975
		Composite	9	5	22·0	308	0·897
C	1	63	6	4	23·3	63	0·963
		125	4	1	21·6	100	0·993
		250	4	2	22·0	61	0·947
		500	5	3	18·2	879	1·000
		Composite	9	5	25·8	45	0·982
	2	63	6	1	15·2	52	0·848
		125	4	5	16.2	64	0.995
		250	4	4	15.9	59	1.000
		500	5	2	22.3	62	0.992
		Composite	9	3	24.2	81	0.991
	3	63	6	3	19·4	25	0·996
		125	4	2	20·5	62	0·881
		250	4	1	36·4	28	0·893
		500	5	4	24·4	60	1·000
		Composite	9	5	29·8	65	0·948

Table 1—(*continued overleaf*)

Table 1—*continued*

Subject	Trial	Central frequency	Acceleration (g)	Order	$\mathrm{TTS}_{v,0}$(dB)	t_c(s)	r^2
D	1	63	6	3	22·8	96	1·000
		125	4	1	22·9	81	1·000
		250	2	2	12·0	195	1·000
		500	6	5	19·9	140	0·892
		Composite	9	4	25·3	98	0·962
	2	63	6	3	26·8	93	0·989
		125	4	5	16·7	55	0·989
		250	4	2	10·3	143	0·985
		500	6	1	22·2	68	0·977
		Composite	10	6	27·5	114	1·000
	3	63	6	2	20·1	61	1·000
		125	4	1	14·2	125	0·894
		250	6	5	18·7	77	0·952
		500	6	4	20·4	138	1·000
		Composite	10.5	3	22·6	93	0·997
E	1	63	6	3	19·9	91	0·910
		125	4	2	40·6	68	0·985
		250	4	1	39·9	62	0·974
		500	5	5	38·8	42	0·981
		Composite	9	4	32·3	80	0·978
	2	63	6	1	20·7	36	0·992
		125	4	5	37·7	43	0·979
		250	4	4	28·9	51	0·944
		500	5	2	28·8	42	0·955
		Composite	9	3	30·0	80	0·980
	3	63	6	2	31·2	45	0·974
		125	4	1	31·7	58	0·986
		250	4	4	30·8	67	0·997
		500	5	5	33·7	60	1·000
		Composite	9	3	35·7	74	0·944
F	1	63	6	2	24·3	129	0·946
		125	4	4	21·9	130	0·973
		250	4	5	28·8	87	0·955
		500	5	1	30·6	72	0·959
		Composite	9	3	29·1	131	0·952
	2	63	6	1	23·9	62	0·991
		125	4	4	26·4	54	0·947
		250	4	2	25·2	79	0·983
		500	5	3	31·5	44	0·993
		Composite	9	5	31·0	56	0·976
	3	63	6	3	18·9	53	0·931
		125	4	2	20·6	70	0·959
		250	4	4	16·2	111	0·919
		500	5	1	32·6	47	1·000
		Composite	9	5	34·8	46	0·994

Table 1—(*continued overleaf*)

TABLE 1—*continued*

Subject	Trial	Central frequency	Acceleration (g)	Order	$TTS_{v,0}$(dB)	t_c(s)	r^2
G	1	63	6	2	34·8	88	0·985
		125	4	1	38·5	57	0·970
		250	4	4	40·9	49	0·991
		500	5	5	31·7	38	0·991
		Composite	9	3	30·7	60	0·991
	2	63	6	2	23·7	47	0·978
		125	4	4	31·0	42	0·993
		250	4	5	35·9	45	0·965
		500	5	1	26·9	58	0·961
		Composite	9	3	32·4	63	0·983
	3	63	6	3	25·2	40	0·955
		125	4	2	21·2	34	0·996
		250	4	1	25·8	54	0·977
		500	5	5	20·3	31	0·985
		Composite	9	4	15·7	62	0·998

table is also shown the acceleration of the vibration level resulting from the composition. In Figure 2 is presented an example of the spectrum of the component one-third octave bands together with the composite vibration exposure condition. A composite broadband vibration and each component one-third octave band vibration to which the subjects were exposed in a random sequence on a certain day are shown in Table 1. One session (a 3 h period in the morning or afternoon with a 10 or 30 min rest period) was repeated for at least three days at the same time for each subject. Thus, the in-between period of exposure was longer than 30 min. This was considered to be sufficiently long to avoid an acute accumulative effect due to vibration exposure, as indicated in the preceding studies [3, 7, 10]. A given $TTS_{v,0}$ can determine each intensity of differnt one-third octave bands on the basis of the mathematical model acquired from regression analysis in the previous studies. The $TTS_{v,0}$ induced by the composite band vibration was compared with the largest $TTS_{v,0}$ induced by the component one-third octave band vibration.

Statistical analyses were carried out using SPSS-X, a Statistical Package for the Social Sciences [9], at the Kyoto University Data Processing Center.

3. RESULTS

3.1. EXPONENTIAL RECOVERY OF VIBRATORY SENSATION THRESHOLD

In Figure 3 is shown an example of the recovery of the vibratory sensation threshold after component and composite vibration exposures. The recovery process is seen to be almost the same as in the preceding studies [3, 7, 10]. All of the vibratory sensation threshold recovered to the prior threshold within 10 min after the exposure. Most regression analyses for each composite vibration also disclosed the goodness of fit of the exponential recovery model:

$$TTS_{v,t} = TTS_{v,0} \exp(-t/t_c), \tag{1}$$

where t is the elapsed time after the cessation of exposure, $TTS_{v,t}$ is the TTS_v at time t, and t_c is a time constant. Those coefficients of determination were as large as 0·977 on average, with a range of 0·897–1·00 (see Table 1). Consequently, the recovery of TTS_v after

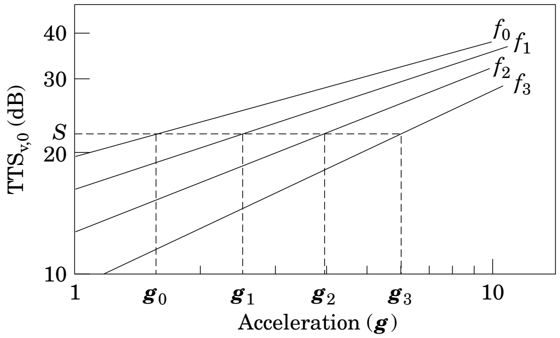

Figure 1. A model of the relationship between the expected $\mathrm{TTS}_{\mathrm{v},0}$ and the accelerations of the four component vibrations. S, An expected $\mathrm{TTS}_{\mathrm{v},0}$; f_0–f_3, the central frequency of the component one-third octave band vibration.

exposure to the composite vibration is also as exponential as that for a single one-third octave band or discrete frequency exposure [7, 10].

3.2. THE RELATIONSHIP BETWEEN $\mathrm{TTS}_{\mathrm{v},0}$ BY COMPOSITE VIBRATION EXPOSURE AND $\mathrm{TTS}_{\mathrm{v},0}$ BY COMPONENT VIBRATION EXPOSURE

In Figure 4 are plotted the relationships between the $\mathrm{TTS}_{\mathrm{v},0}$ ($\mathrm{TTS}_{\mathrm{v},0}$-C) due to exposure to the composite vibration and the largest $\mathrm{TTS}_{\mathrm{v},0}$ ($\mathrm{TTS}_{\mathrm{v},0}$-E) due to one-third octave band vibration. Those mean values were 28·1 and 26·2 respectively. However, three-way analysis of the variance of the $\mathrm{TTS}_{\mathrm{V}}$ with factors of composition, subject and repetition disclosed no significant difference in the $\mathrm{TTS}_{\mathrm{V}}$ between the composite vibration and the most effective one-third ocatve band component ($P < 0{\cdot}05$) as shown in Table 2. According to Figure 4, we postulated that the relationship between $\mathrm{TTS}_{\mathrm{v},0}$-C and $\mathrm{TTS}_{\mathrm{v},0}$-E is linear:

$$\mathrm{TTS}_{\mathrm{v},0}\text{-C} = a \times \mathrm{TTS}_{\mathrm{v},0}\text{-E} + p, \tag{2}$$

where a and p are constants.

The coefficients of determination in the regression analysis were as large as 0·652 for equation (1). The regression lines obtained suggest that $\mathrm{TTS}_{\mathrm{v},0}$-C and $\mathrm{TTS}_{\mathrm{v},0}$-E are almost equal under the given experimental conditions. Thus we postulated that $\mathrm{TTS}_{\mathrm{v},0}\text{-C} = \mathrm{TTS}_{\mathrm{v},0}\text{-E}$, and statistically tested a null hypothesis, that is, $a = 1$ and $p = 0$ in equation (2). However, the test rejected the null hypothesis at the significance level of 1%. The test yielded $a = 0{\cdot}639$ and $p = 8{\cdot}293$. The equation obtained shows that a condition expected

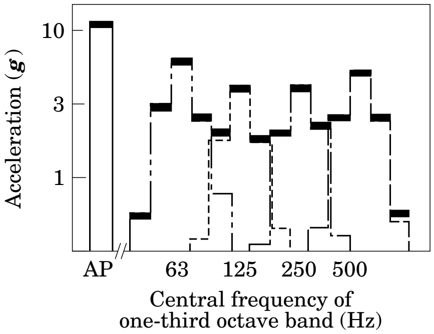

Figure 2. An example of the acceleration level distributions of four component one-third octave band vibrations and their composite vibration (AP).

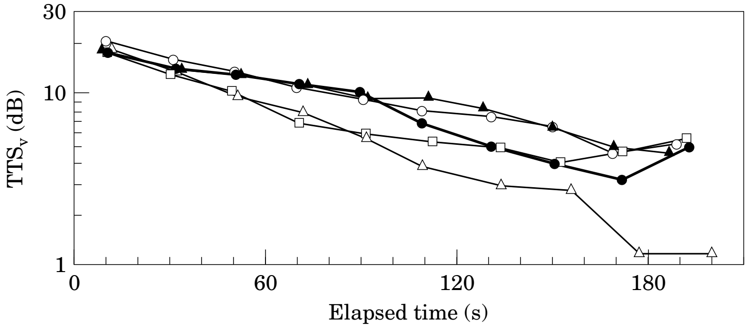

Figure 3. The recovery process of TTS_V for a subject on a certain day (first trial of subject A in Table 1) after 2 min clasping of handle (tested frequency for threshold 125 Hz, 0 dB = 1 $\mu m^{p\text{-}p}$, grasping power = 40 N). —□—, 63 Hz, 6-; —△—, 125 Hz, 4*g*; —▲—, 250 Hz, 4*g*; —○—, 500 Hz, 5*g*; —●—, composite, 10*g*.

to induce a $TTS_{v,0}$ of 15 dB may result in a $TTS_{v,0}$ of 18·7 dB, and a condition greater than 22·9 dB may result in a smaller $TTS_{v,0}$ value than expected.

These results imply that the composition with four one-third octave band vibrations did not significantly increase the $TTS_{v,t}$.

3.3. THE RELATIONSHIP BETWEEN THE TIME CONSTANT ONE TO COMPOSITE VIBRATION EXPOSURE AND THAT DUE TO COMPONENT VIBRATION EXPOSURE

In Figure 5 are plotted the relationships between the largest t_c(t_c-E) due to one-third octave band vibration and the t_c(t_c-C) due to exposure to the composite vibration. The mean values were 110·0 and 91·0, respectively. Three-way analysis of the variance of t_c with factors of composition, subject and repetition disclosed a significant difference in t_c between the composite vibration and the most effective component one-third octave band to prolong the recovery ($P < 0{\cdot}01$) as shown in Table 3. According to Figure 5, we postulated that the relationship of t_c-C to t_c-E is linear,

$$t_c\text{-C} = b \times t_c\text{-E} + q, \qquad (3)$$

where b and q are constants, except for the two extreme values of more than 300 s. The coefficients of determination in the regression analysis were as large as 0·521.

The analysis yielded $b = 0{\cdot}519$ and $q = 33{\cdot}9$. This equation shows that a condition expected to induce a t_c larger than 70·5 may result in a smaller t_c value than expected.

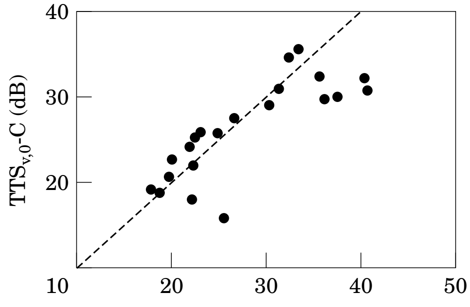

Figure 4. The relationship of the $TTS_{v,0}$ due to composite vibration ($TTS_{v,0}$-C) with the maximum $TTS_{v,0}$ due to component vibration ($TTS_{v,0}$-E) (tested frequency for threshold 125 Hz, 0 dB = 1 $\mu m^{p\text{-}p}$, grasping power = 40 N). – – – –, $TTS_{v,0}$-C = $TTS_{v,0}$-E.

Table 2

A three-way analysis of variance for TTS$_{v,0}$. *Composite*: *composite vibration and the most effective component one-third octave band vibration*

Source	df	Sum of squares	Deviance	F-value	P-value
Composite	1	35·3	35·3	1·699	0·2017
Subject	6	1 071·9	178·7	8·609	0·0001
Repetition	2	10·8	5·4	0·259	0·7732
Residual	32	664·0	20·8	–	–
Total	41	1 782·0	–	–	–

These results imply that the composition with four one-third octave band vibrations did not significantly increase the values of t_c.

3.4. THE RELATIONSHIP t_c AND THE TTS$_{v,0}$ FOR COMPOSITE VIBRATION EXPOSURE

The relationship between t_c and the TTS$_{v,0}$ for all composite vibration exposures is examined in Figure 6. The overall correlation coefficient between t_c and the TTS$_{v,0}$ was 0·447: without the extreme values of t_c above 300 s, it was $-0·526$.

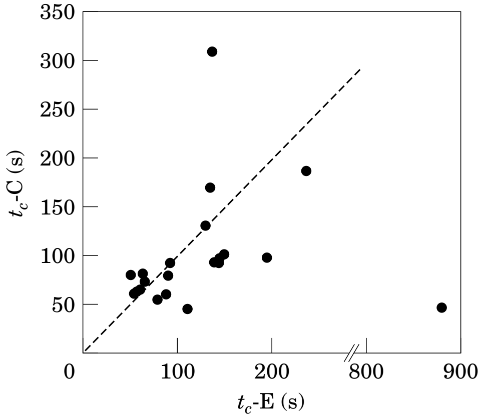

Figure 5. The relationship of t_c due to composite vibration (t_c-C) with the maximum t_c due to component vibration (t_c-E) (tested frequency for threshold 125 Hz, grasping power = 40 N). ————, t_c-C = t_c-E.

Table 3

A three-way analysis of variance for t_c. Composite: composite vibration and the most effective component one-third octave band vibration

Source	df	Sum of squares	Deviance	F-value	P-value
Composite	1	4 751·3	4 751·4	7·917	0·0086
Subject	6	45 059·2	7 509·9	12·513	0·0001
Repetition	2	8 559·7	4 279·9	7·131	0·0029
Residual	30	18 005·1	600·2	–	–
Total	39	78 332·0	–	–	–

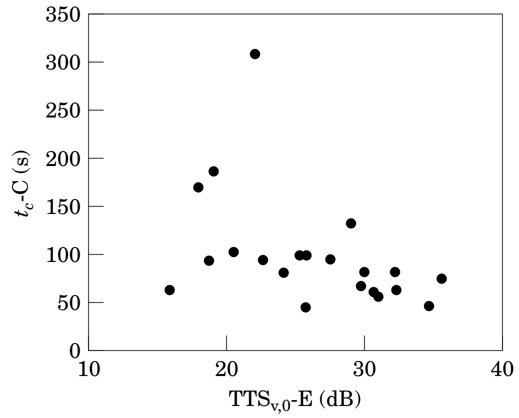

Figure 6. The relationship of t_c with $TTS_{v,0}$ (tested frequency for threshold 127 Hz, 0 dB = 1 μm^{p-p}, grasping power = 40 N).

4. DISCUSSION

4.1. THE EFFECT OF COMPOSITE VIBRATION ON THE $TTS_{v,0}$

The exposure vibration composed of the four different component vibrations had much larger acceleration than in the preceding study [10]. Thus, the $TTS_{v,0}$ triggered by the component vibrations actually to increase, and the $TTS_{v,0}$ induced with the magnitude of the composite vibration expected for the envisaged acceleration, it would be significantly higher than the $TTS_{v,0}$ observed post-exposure. However, the result did not show any significant increase in the $TTS_{v,0}$ due to exposure to composite vibration, although the exposed vibration energy clearly increased due to being composed of the four one-third octave vibrations. The component vibrations, that should maximize the overall level of acceleration and induce the same $TTS_{v,0}$, brought about no significant increase in the $TTS_{v,0}$. This means that there is no significant multiplicative or additive effect on $TTS_{v,0}$ due to composite vibration compared with that due to component vibration. It suggests more strongly than the preceeding study [10] that the $TTS_{v,0}$ induced by broadband vibration exposure may equal that induced by exposure to component vibration with a narrow band.

The ISO has adopted the dose–response relationship of human exposure to vibration transmitted to the hand in terms of frequency-weighted energy-equivalent acceleration [11, 12]. This implies that the broader band exposure vibration causes the worse effect on workers' health. However, with regard to the deleterious effect of the local broadband vibration on workers' health, on the basis of the results that we have obtained for $TTS_{v,0}$, the effect of such broadband exposure would be no greater than those induced by the component band exerting the most adverse influence. In this context, our result suggests that the ISO standard protects workers from TTS_V induced by local vibration exposure. There may, however, be a problem in our study as to whether the accuracy and precision are sufficient to detect an increment in the vibratory sensation threshold. The subjective variables inherent in psycho-physical measurement pose a major risk of error. Such variance or error could not be avoided, even though we used subjects well trained to take part in the measurement of vibratory sensation threshold. For example, there was one subject whose $TTs_{v,0}$ was larger after composite vibration exposure than after component vibration exposure. It is not clear whether such phenomena are due to chance or to the individual characteristics of certain subjects. Further study involving a composite vibration with more one-third octave bands and the participation of more subjects may establish the validity of our results.

From the present results, it can be considered that the vibratory sensation mechanism is affected by a majority decision system that determines the TTS_V induced by the most effective component band composing the exposure vibration. However, we do not understand sufficiently the physiological mechanism relating to TTS_V. Lündstrom [13] and Lündstrom and Johansson [14] have studied the thresholds of single mechano-receptive afferent units, enervating the glabrous skin of the human hand to sinusoidal skin indentations. They concluded that the acute impairments to tactile sensibility caused by vibration exposure, as observed in psychological studies, may be explained by an influence on the excitability of tactile units such as Pacinian corpuscles. O'Mara *et al.* [15] studied peripheral and central neural contributions to vibrotactile adaption in decerebrated or anesthetized cats. They recorded impulses from sensory nerve fibers associated with Pacinian corpuscle receptors and those from central neurons of the dorsal column nuclei that received their input from vibration-sensitive receptors of the forelimb footpads. They observed that the adaptation in Pacinian corpuscle fiber responses showed a similar exponential time course in both cutaneous and mesenteric Pacinian corpuscle fibers. Thus they concluded that it was unlikely for mechanical changes in the skin to contribute significantly to vibratory adaption in Pacinian corpuscle fiber response. They observed a long-term response depression in cuneate neurons following their prior activation for inputs from unconditioned sites within the neuron's excitatory receptive field, as well as from the conditioned site. They suggested that the response adaptation was attributable to changes in the central neuron. On the other hand, the excitation of cuneate neurons seems to be inhibited by complex pathways. Stimulation of the sensorimotor cortex has both an excitatory and an inhibitory influence on cuneate neurons [16]. Cortical excitatory action seems to be concentrated in the interneurons of the cuneate and gracile nuclei [17]. These complicated excited mechanisms of primary and central neurons seem relevant to our findings for $TTS_{v,0}$ following exposure to composite vibration, as well as to the response characteristics of mechano-receptors themselves during broadband random vibration. It is necessary further to study these factors in order to discover why the exposure to composite vibrations did not increase the $TTS_{v,0}$.

A longer exposure than ours, or repeated exposure, may also cause the increase in the $TTS_{v,0}$. Thus there is a need for further study of the $TTS_{v,0}$ under such conditions.

4.2. THE EFFECT OF COMPOSITE VIBRATION ON t_c

The t_c differed depending on the characteristics of the vibration and the subject. As shown in Figure 6, the larger $TTS_{v,0}$ seems to relate to the smaller t_c under composite broadband vibration exposure. In the preceding studies [3, 10], there was no such trend, and the plot was scattered broadly and unsystematically. This result suggests the need for further study to establish convincingly such a difference and to disclose the quantitative relationship by assuring more careful physiological control of the condition of subjects after, as well as during, exposure.

CONCLUSIONS

1. The TTS_V due to hand–arm vibration composed of one-third octave bands recovers exponentially as well as a component one-third band vibration.
2. The $TTS_{v,0}$ and the time constant t_c yielded by the composite vibration exposure do

not significantly exceed the maximum $TTS_{v,0}$ induced by the most effective component vibration exposure.

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REFERENCES

1. G. GEMNE 1994 *Scandinavian Journal of Work and Environmental Health* **20**, special issue, 90–99. Where is the research frontier for hard–arm vibration?
2. M. J. GRIFFIN 1990 *Handbook of Human Vibration*. London: Academic Press.
3. K. NISHIYAMA, K. TAODA, H. YAMASHITA and S. WATANABE 1994 *International Archives of Occupational and Environmental Health* **66**, 97–102. Application of a new, self-recording, vibratory sensation meter to measure temporary threshold shift of vibratory sensation caused by local vibration exposure.
4. S. MAEDA and Y. KUME 1989 *Journal of the Japanese Industrial Management Association* **40**, 336–342. Temporary threshold shift on finger-tip vibratory sensation induced by exposure to spectrum vibration.
5. N. HARADA 1978 *Japanese Journal of Hygiene* **33**, 699–705. Studies on the changes in the vibratory sensation threshold at the fingertip in relation to some physical parameters of exposed vibration, part 1: a study on the methods of vibration exposure and measurement of the vibratory sensation threshold.
6. N. HARADA 1978 *Japanese Journal of Hygiene* **33**, 706–717. Studies on the changes in the vibratory sensation threshold at the fingertip in relation to some physical parameters of exposed vibration, part 2: a study on the equal TTS curves of the vibratory sensation and hygienic allowable limit of a portable mechanized tool.
7. K. NISHIYAMA and S. WATANABE 1981 *International Archives of Occupational and Environmental Health* **49**, 21–33. Temporary threshold shift of vibratory sensation after clasping a vibrating handle.
8. N. HARADA and M. J. GRIFFIN 1991 *British Journal of Industrial Medicine* **48**, 185–192. Factors influencing vibration sense threshold used to assess occupational exposures to hand transmited vibration.
9. SPSS INC. 1988 *SPSS-X User's Guide*. SPSS Inc.; third edition.
10. K. NISHIYAMA, K. TAODA, H. YAMASHITA and S. WATANABE 1995 *International Archives of Occupational and Environmental Health* **68**, 255–261. The temporary threshold shift of vibratory sensation induced by the composite vibration exposure.
11. ISO/TC 180/SC 4/WG 3 1973 *Guide for the Evaluation of Human Exposure to Hand-transmitted Vibration*.
12. ISO/TC 180/SC 4/WG 3 1983 *Second Draft International Standard* ISO/DIS 5349, *Guide for the Measurement and the Assessment of Human Exposure to Vibration Transmitted to the Hand*.
13. R. LŬNDSTROM 1986 *Scandinavian Journal of Work and Environmental Health* **12**, 413–416. Responses of mechanoreceptive afferent units in the glabrous skin of the human hand to vibration.
14. R. LŬNDSTROM and R. S. JOHANSSON 1986 *Ergonomics* **29**, 687–698. Acute impairment of the sensitivity of skin mechanoreceptive units caused by vibration exposure of the hand.
15. O. O'MARA, M. J. POWE and R. P. C. TARVIN 1988 *Journal of Neurophysiology* **59**, 607–622. Neural mechanisms in vibrotactile adaptation.
16. M. CARRERAS, J. LEVITT, W. CHAMBERS and C. N. LIU 1960 *Anatomical Record* **136**, 174–175. Unit activity in the posterior column nuclei and corticofugal influence upon it.
17. P. ANDERSON, J. P. ECCLES, R. F. SCHMIDT and T. YOKOTA 1964 *Journal of Neurophysiology* **27**, 1080–1095. Identification of relay calls and interneurons in the cuneate nucleus.