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Original Article

Dependency of Temporary Threshold Shift of Vibratory Sensation in Fingertip on 1/3 Octave-Band Hand-Arm Vibration Exposure Period

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Abstract

Objectives: To investigate the dependency of temporary threshold shift of vibratoty sensation (TTS_v) in fingertip on hand-arm vibration exposure period.

Methods: Six healthy students were instructed to grip a vibrating or nonvibrating handle in the experimental room. The gripping force was 40 N. The vibratory sensation threshold at 125 Hz was measured before and after the exposure in the exposed middle fingertip. The exposure vibration was vertical and the 1/3 octave-band vibration with had a central frequency of 200 Hz and an intensity of 39.2 m/s^2. The exposure periods were 8, 15, 30, 60, 120, 240 and 600 s. $TTS_{v,t}$ was evaluated as the difference in vibratory sensation threshold between immediately before and t seconds after the exposure.

Results: TTS_v recovered exponentially as in several previous studies and its use enabled us to estimate the time constant and $TTS_{v,0}$. $TTS_{v,0}$ with vibration exposure was significantly larger than that without it. The regression analysis of the relationship between vibration exposure period (T) and $TTS_{v,0}$ (T) for each subject confirmed the good fit of the equation $TTS_{v,0}(T) = B_0 + B_1 * Log_{10}(T)$, where B_0 and B_1 are the calculated constants (adjusted $R^2 = 0.56 - 0.87$). The time constants did not show such a clear dose effect relationship of exposure period as $TTS_{v,0}$.

Conclusion: The dependency of $TTS_{v,0}$ on vibration exposure period was asymptotically proportional to the logarithm of gripping period. To more quantitatively confirm the relationship of the time constants for recovering time course of TTS_v, it maybe necessary to improve the measurement method for TTS_v.

Key words: vibratory sensation, temporary threshold shift, vibration syndrome, exposure period, hand-arm vibration

Introduction

The objective of a series of our systematic studies of the temporary threshold shift of vibratory sensation (TTS_v) (1–5) has been to clarify the relationship between TTS_v induced by acute hand-transmitted vibration and the pathological effects of long-term hand-transmitted vibration exposure on the permanent threshold shift of vibratory sensation. During our study, a new permissible limit for the health protection of workers exposed to hand-transmitted vibration was established by the International Organization for Standardization (ISO) (6). It is based on some epidemiological studies of the dose-response association between vibration exposure and vibratory white finger (VWF) prevalence.

One of the other typical findings of the hazard caused by hand-transmitted vibration is an abnormal permanent threshold shift of vibratory sensation. Although the methods of measuring vibrotactile perception thresholds in the fingertips for the assessment of nerve dysfunction, particularly the permanent threshold shift observed among workers exposed to hand-transmitted vibration, has been defined by ISO (7), the relationship between nerve dysfunction and temporal peripheral threshold shift of vibratory sensation has been hardly discussed. The pathological mechanism of the hypoesthesia of vibratory sensation in vibration syndrome remains in vague in comparison with that of auditory TTS and noise-induced permanent threshold shift (NIPTS) (8).

Furthermore, the procedure for evaluating the dose of exposure to hand-transmitted vibration uses almost the same the

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frequency weightings based on equal sensation contours of vibratory stimulation. We thought that such frequency weightings should be based on more pathological effects such as the vibration-induced threshold shift of vibratory sensation induced by hand-transmitted vibration. Many researchers have demonstrated the temporary threshold shift of peripheral sensory perception in the fingertips following exposure to hand-arm vibration (9–11).

Malchaire et al. (12, 13) studied the evolution of vibration perception threshold (VPT) induced by exposure to vibration of 32 min period with frequent interruptions of approximately 60 s. However, according to our studies, 60 s interruptions might be sufficient to recover VPT and result in a lower TTS_v than that observed in our present study. TTS may not accumulate but clear near the residual fraction of TTS during rather long interruptions. Thus, the use of an equation model of TTS under such interruptions might be underestimated for evaluating the dependency of TTS on continuous vibration exposure period. We have addressed the importance of identifying the time constant for each exposure. However, it is difficult to further discuss the time constant because it showed too large variance for each subject and experimental condition.

We attempted to more quantitatively evaluate TTS_v induced by an experimental exposure of hand-transmitted vibration in the laboratory, developed a self-recording vibratory sensation meter and found that $TTS_{v,t}$ induced by the exposure of hand-arm vibration recovered exponentially according to the regression model (1–5),

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

where t is the elapsed time after the cessation of exposure, $TTS_{v,t}$ is TTS_v at time t and t_c is time constant. $TTS_{v,t}$ is the difference between the vibration sensation threshold (in dB) measured just before and t seconds after each exposure. The regression analysis could well define $TTS_{v,0}$ and t_c. Using $TTS_{v,0}$, we established the mathematical relationships of TTS_v with not only with the elapsed time after the cessation of exposure but also other parameters such as the frequency and intensity of the exposure vibration, and the force gripping the vibrating handle. We also determine how to estimate $TTS_{v,0}$ and t_c after exposure to 1/3 octave-band vibration with different central frequencies. However, previous studies did not systematically include a parameter related to hand-arm vibration exposure period. Therefore, the objective of this study was to clarify the quantitative dependency of $TTS_{v,0}$ on vibration exposure period.

Subjects and Methods

The subjects were six healthy male students who gave informed consent after being sufficiently informed about the experiment, aged 20–24 years (mean 22 years) who were engaged in nonstrenuous manual work and had normal vibratory sensations (125 Hz, less than or equal to 5.0 dB, 0 dB=125 m^{p-p}). The experiment was carried out in a sound- and vibration-proof chamber maintained at 22°C, from April 1990 to August 1991. The subjects were free to withdraw at any time during the course of the experiment.

Each subject was seated, and allowed to acclimatize to the chamber's climate. He kept his left hand grip on a metallic handle attached to an electrodynamic vibrator with a 40 N gripping power and a 0.0 N push-pull power during a given time. An electric heater warmed the handle to 32°C in order to prevent the exposed hand from cooling. The grip began only after the subject had shown a stable vibratory sensation threshold and a skin temperature of the fingertips of 30°C or more for 15 min at least.

Vibratory sensation threshold was measured using the self-recording vibratory sensation meter developed in a previous study (2). The measurement proceeded under a test frequency of 125 Hz with a contact pressure of the left middle fingertip at 1.0 N and the velocity of vibratory level change at 1.25 dB/s.

The handle was vibrated vertically (z direction) with a 1/3 octave-band vibration with a central frequency of 200 Hz and an intensity of 39.2 m/s^2 by an electrodynamics vibrator (IMV Co., Japan). The control condition was to grip the same handle that was not vibrating. The gripping periods on a certain day were 8, 15, 30, 60, 120, 240 and 600 s. One session 3 1/2 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.

According to the preliminary experiment, more threshold measurements after exposure were taken as more times as possible than those of previous studies: at 15 s intervals for the first 1 min following cessation of gripping, 20 s intervals for the next 2 min, and 1 min intervals for the last 7 min. The skin temperature of some fingertips of both hands was measured simultaneously for reference. The regression analyses used the values of $TTS_{v,t}$ obtained 3 min after the cessation of gripping, just before decreasing below 0 dB and before the phase of bounce of TTS_v, that is, a pause in the decrease or a gentle and transient increase in vibratory sensation threshold. The other experimental procedures were the same as those in previous studies (2, 4, 5).

Statistical analyses were carried out at the Kyoto University Data Processing Center using SPSS or SAS (4, 15). The repeated measures analysis of variance was carried out on response variables using the subprogram GLM Repeated Measures Procedure of SPSS. If the significance was confirmed by this subprogram, the Student-Newman-Keuls (SNK) and Bonferoni tests were performed based on a significance level of $p<0.05$ for a posteriori contrast to examine type 1 error in order to compare all possible pairs of group means. If the execution of the subprogram suggested some dose effect relationship of $TTS_{v,0}$ with gripping period, regression analysis was carried out using the REG Procedure of SAS.

Results

Exponential recovery of vibratory sensation threshold

The recovery is seen to be almost the same as that in the previous studies (1–5). The entire vibratory sensation threshold recovered to the prior threshold within 10 min after gripping. However, some subjects or conditions showed the bounce in the threshold during the recovery at approximately 3 min or more, similar to that in previous studies (1–5). Thus, in the following procedure, we adopted the $TTS_{v\,(t)}$ before such a bounce as mentioned in the Methods. Most regression analyses for each grip also disclosed the good fit of the exponential recovery model (1). The adjusted coefficients of determination were as large as 0.98 on average, with a range of 0.90–1.00. Consequently, the recovery of TTS_v is as exponential as that in previous studies (2–5).

Relationship between $TTS_{v,\,0}$ and gripping period

Figure 1 shows a plot of the relationship between $TTS_{v,\,0}$ and vibration exposure period by subject. From Figure 1, the average $TTS_{v,\,0}$ increases monotonously with an increase in vibration exposure period although, during first 8 s, most of the subjects showed the largest increase in $TTS_{v,\,0}$. $TTS_{v,\,0}$ was approximately 15 dB on average. $TTS_{v,\,0}$ after 10-min vibration exposure was approximately 35 dB on average. Figure 2 shows a plot of the relationship between $TTS_{v,\,0}$ and the period of gripping the nonvibrating handle by subject. $TTS_{v,\,0}$ after 10-min gripping was approximately 10 dB on average. From Figure 2, the increase without vibration exposure seems not to show a very monotonous increase as at with vibration exposure. High $TTS_{v,\,0}$ values after 4 and 10 min are observable, but the statistical analysis showed no significant differences. If the sample size or the number of repetition is increased, one

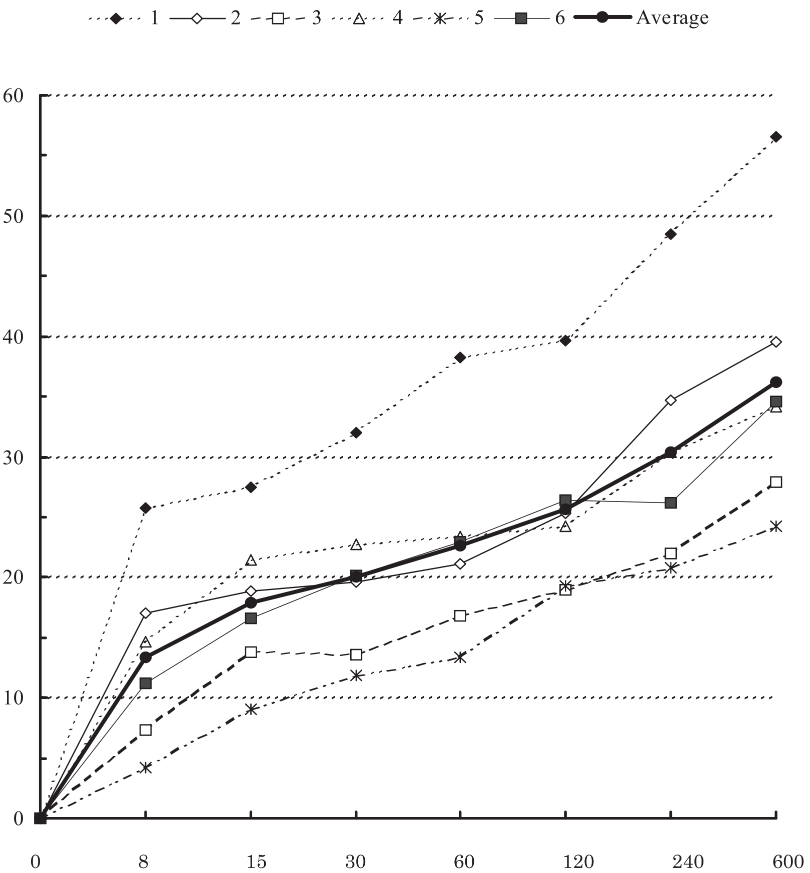

Fig. 1 Average relationships between $TTS_{v,\,0}$ and vibration exposure period by subject (tested frequency for threshold=125 Hz, 0 dB= 1 mm^{p-p}, gripping power=40 N, and exposure vibration: 200 Hz and 39.2 m/s^2). Abscissa: Exposure period (s). Ordinate: $TTS_{v,\,0}$ (dB).

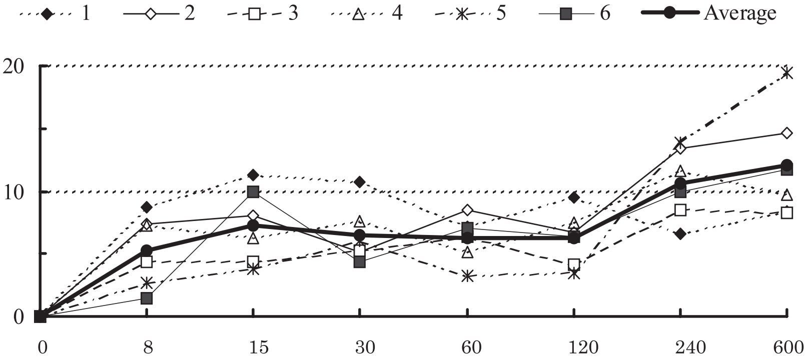

Fig. 2 Average relationships between $TTS_{v,\,0}$ and gripping period without vibration exposure by subject (tested frequency for threshold=125 Hz, 0 dB=1 mm^{p-p} and gripping power=40 N). Abscissa: Exposure period (s). Ordinate: $TTS_{v,\,0}$ (dB).

Table 1 Repeated measures analysis of variance of $TTS_{v,0}$. Gripping period: 8, 15, 30, 60, 120, 240 and 600 s. Exposure: With and without vibration exposure (tested frequency for threshold=125 Hz, gripping power=40 N, and exposure vibration: 200 Hz and 39.2 m/s²)

Source	df	Sum of squares	Deviance	F-value	p-value
Intercept	1	56929.7	56929.7	444.5	0.000
Exposure	1	13938.7	13938.7	108.8	0.000
Period	6	4886.0	814.3	6.4	0.000
Exposure*Period	6	1593.9	265.7	2.1	0.069
Residual	63	8067.9	128.1	–	–

may find not only significant differences among different periods of gripping but also a monotonous increase in $TTS_{v,0}$. The difference in $TTS_{v,0}$ after 10-min gripping between with and without vibration exposure was approximately 25 dB. As shown in Table 1, the repeated measures variance of analysis showed the statistically significant effects of vibration and gripping periods and the significant interaction between exposure and gripping periods ($p<0.001$). As shown in Table 2, the subprogram suggests the significant dose effect of the period of gripping the vibrating handle on $TTS_{v,0}$. However, no such clear dose effect was observed in the case of gripping the nonvibrating handle. The right column of Table 2 shows that the significant effect of the vibration exposure might begin after approximately 15 s of gripping.

Figure 1 suggests an equation model as described in

$$TTS_{v,0}(T) = B_0 + B_1 * \text{Log}_{10}(T) \qquad (2)$$

where B_0 and B_1 are constants to be acquired by regression analysis. Table 3 shows the obtained coefficients, those standard errors and coefficients of determination for six subjects, respectively ($p<0.0001$). The coefficient of determination was 0.39 for all the subjects but that for each subject was improved and its range was from 0.55 to 0.87.

Relationship between t_c and gripping period

Figure 3 shows the relationship between t_c and vibration exposure period by subject. The average t_c tended to increase with an increase in vibration exposure period although the variance was rather large. The average t_c after 10-min griping was approximately 100 s at most. Figure 4 shows no such relationship between t_c and the period of gripping the nonvibrating handle. The increase in t_c was less clear than that after vibration exposure and the variance was larger. The average t_c was approximately 50 s. As shown in Table 4, the repeated measures analysis of variance does not show any statistically significant effects of gripping period and vibration exposure ($p<0.05$).

The overall correlation coefficient between t_c and $TTS_{v,0}$ was −0.13 ($p<0.05$).

Table 2 Mean $TTS_{v,0}$ (dB) by vibration exposure and gripping period (s) and repeated measures analysis of variance $TTS_{v,0}$ (tested frequency for threshold=125 Hz, 0 dB=1 mm^{p-p}, gripping power=40 N, and exposure vibration: 200 Hz and 39.2 m/s²)

Exposure	With							Without	Significance levels between exposed and not-exposed***
Period (s)	$TTS_{v,0}$	Subgroups** (Post hoc multiple comparison test)			15	30	60	$TTS_{v,0}$	
8	13.3	1			–	–	–	6.8	0.202
15	17.9	1	2		–	–	–	6.7	0.006
30	20.0	1	2		–	–	–	6.5	0.001
60	22.8	1	2		–	–	–	6.9	0.003
120	25.6	1	2	3	–	–	–	6.3	0.000
240	30.4		2	3	*	–	–	10.4	0.002
600	37.2			3	*	*	*	12.1	0.000
Significance level**		0.107	0.095	0.057					

* $TTS_{v,0}$ significantly differs between different exposure periods at $p<0.05$ by Bonfferoni adjusted significance level. –: Not significant.
** Student-Newman-Keuls's test.
*** Bonferoni adjusted significance level.

Table 3 Parameters for variable intercept and vibration exposure period (T) estimated by regression analysis for $TTS_{v,0} = B_0 + B_1 * LOG_{10}(T)$ ($p<0.0001$, tested frequency for threshold=125 Hz, 0 dB=1 mm^{p-p}, gripping power=40 N, and exposure vibration: 200 Hz and 39.2 m/s², gripping period: 8, 15, 30, 60, 120, 240 and 600 s)

Subject code	Variable		Standard error for variables		Adjusted R^2
	Intercept (B_0)	Exposure period (B_1)	B_0	B_1	
1	38.0	16.56	3.315	2.048	0.545
2	25.0	12.24	1.931	0.927	0.662
3	17.0	9.70	0.917	0.567	0.846
4	24.2	9.00	0.899	0.556	0.832
5	15.3	12.83	1.103	0.682	0.874
6	22.4	11.08	1.740	1.075	0.664
All	23.7	11.90	1.313	0.811	0.394

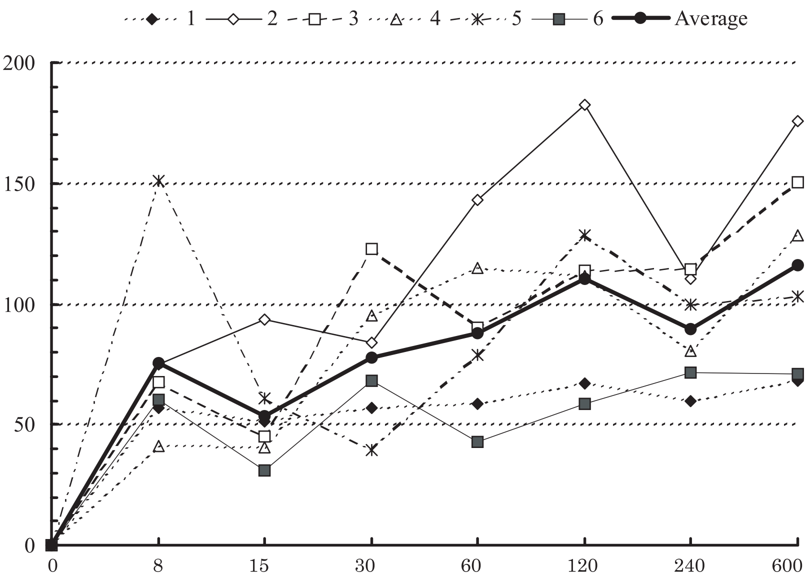

Fig. 3 Average relationships between t_c and vibration exposure period by subject (tested frequency for threshold=125 Hz, 0 dB= 1 mm^{p-p}, gripping power=40 N, and exposure vibration: 200 Hz and 39.2 m/s^2). Abscissa: Exposure period (s). Ordinate: t_c (s).

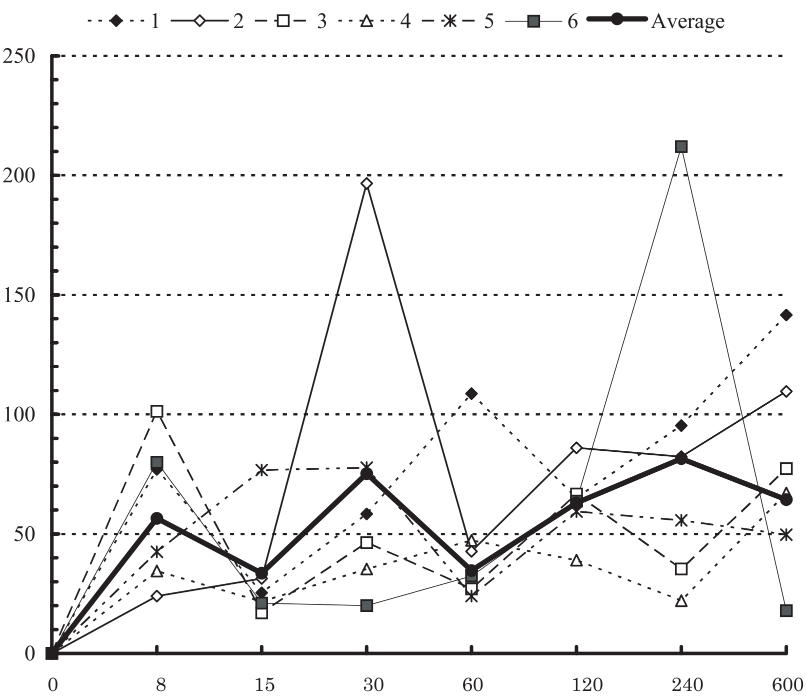

Fig. 4 Average relationships between t_c and gripping period without vibration exposure by subject (tested frequency for threshold= 125 Hz, 0 dB=1 mm^{p-p} and gripping power=40 N). Abscissa: Exposure period (s). Ordinate: t_c (s).

Table 4 Repeated measures analysis of variance of t_c. Gripping period: 8, 15, 30, 60, 120, 240 and 600 s. Exposure: With and without vibration exposure (tested frequency for threshold= 125 Hz, gripping power=40 N, and exposure vibration: 200 Hz and 39.2 m/s^2)

Source	df	Sum of squares	Deviance	F-value	p-value
Intercept	1	2142648.0	2142648	26.1	0.000
Exposure	1	25773.6	25773.6	0.3	0.573
Period	6	889169.0	148195	1.8	0.114
Exposure*Period	6	568270.0	94711.6	1.2	0.344
Residual	63	5187467.0	82340.7	–	–

Discussion

Dependency of $TTS_{v,0}$ on period of vibration exposure

A previous study (2) has developed the algorithm for predicting $TTS_{v,0}$, but it does not involve a parameter related to vibration exposure period, unlike the present study. In this study, we adopted equation (2) as a regression model for each subject and improved the coefficient of determination in comparison with the coefficient of determination for all subjects. However, it was not as large as the other parameters studied previously (2, 4) because of the large variance in the same subject and under the same experimental conditions. The shorter gripping period did not necessarily result in a lower variance. The shorter gripping period generally resulted in the quicker recovery of TTS_v and the smaller sample size of $TTS_{v,t}$ that were available for regression analysis. This situation might lead to fluctuations in $TTS_{v,0}$ and t_c more easily. The present result suggests the need for development of a vibratory sensation meter design for repositioning skin area to be measured, probe tip geometry, skin stimulator contact force, surround of stimulator, psychological algorithm and so on. Precise test methods for the measurement of what in the fingertips specified by ISO (7) can be examined to solve such a problem, although they were developed only for the chronic threshold shift of vibrotactile perception.

Table 2 shows the observable increase in $TTS_{v,0}$ according to the increase in gripping period, but it is not significant for shorter exposure periods. More than 4-min gripping without vibration exposure also seems to cause a significantly high $TTS_{v,0}$. Additionally, more repetitions of the same experiment for each subject might be needed for observing significant increase of $TTS_{v,0}$.

The present study confirmed the good fit of equation (2) (12, 13) proposed a first-order system for the evolution of VPT, but did not show and discuss the result of its regression analysis. Therefore, it is difficult to compare both studies quantitatively. The first-order system modeled by Malchaire et al. is thought to show the upper limit of TTS_v. Some subjects seemed to feel the test vibration in the forearm instead of in their exposed fingertips after strong vibration or long vibration exposure in our experiments. Thus, VPT does not necessarily mean the sensation in a certain fingertip. Such a situation might result in saturation to the ceiling values of $TTS_{v,0}$. Equation (2) may be valid until certain exposure period when such saturation is measured.

Our empirical equations derived from several regression analyses in the present and previous studies suggest the availability of the following integrated model equation (3). First, it is possible and necessary to examine this model by merging the experimental data obtained from these studies.

$$TTS_{v,t} = k \times \{1 - \exp(k_f \times F)\} \times G^z \times T^B \times \exp(-t/t_c) \quad (3)$$

where G is the intensity of the exposure vibration, F is the gripping force, T is the gripping period, t is the elapsed time after stopping the grip of a vibrating handle and k, k_f, z, B and t_c are constants which should be determined by regression analysis with some $TTS_{v,t}$, values measured.

The previous study shows that the TTS_v is at most 10 dB after 10-min of gripping the nonvibrating handle (4). If we take this value as the threshold, for example, to cause an excessive increase in TTS_v induced by vibration exposure, the equation can estimate the allowable limit duration of vibration exposure under the given tool operation. The present study, however, has not yet clarified the effect of repeated exposures at such an intensity. To clarify the development of the permanent threshold shift of vibratory sensation, it may be necessary to do such further experimental and epidemiological studies.

A series of our systematic studies of TTS_v participated by approximately 30 male students finally clarify the integrated equation approximating the dynamics of TTS_v. The results of these experimental studies suggest that an increase in sample size or a change in population clarifies the statistical distribution of the parameters in equation (3) but it does not change the function form as equation (3). However, it is necessary to conduct further experimental studies to confirm this speculation.

Dependency of t_c on vibration exposure period

Although the result shows that there is a significant difference in t_c between different gripping periods and that t_c seems to increase with gripping period after long vibration exposure, it does not confirm their monotonous relationship. This might be a result of the larger variance caused by the test methods, as mentioned for $TTS_{v,0}$. t_c also differed depending on the characteristics of the vibration and subject. A larger $TTS_{v,0}$ seems to relate to coincide with a smaller t_c. However, there was no such correlation or trend observed, and the plot scattered broadly and unsystematically, as in previous studies (2–5). As mentioned above, the variances of t_c and $TTS_{v,0}$ are relatively large in comparison with those in previous studies. The improvement in measuring system of the threshold as mentioned above might decrease such variances. Therefore, it is necessary to further study TTS_v to establish convincingly such a difference and to clarify the quantitative relationship of TTS_v and vibration exposure period by ensuring more careful physiological control of the conditions of the subjects after as well as during vibration exposure.

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