A Study on the Relationship between Subjective Unpleasantness and Body Surface Vibrations Induced by High-level Low-frequency Pure Tones

Yukio TAKAHASHI^{1, 2*}, Kazuo KANADA¹, Yoshiharu YONEKAWA¹ and Noriaki HARADA²

¹Department of Human Engineering, National Institute of Industrial Health, 6-21-1 Nagao, Tama-ku, Kawasaki 214-8585, Japan

²Department of Hygiene, Yamaguchi University School of Medicine, 1-1-1 Minami-kogushi, Ube, Yamaguchi 755-8505, Japan

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Abstract: Human body surface vibrations induced by high-level low-frequency pure tones were measured at the chest and the abdomen. At the same time, the subject rated the unpleasantness that he had just perceived during the exposure to low-frequency noise stimulus. Examining the relationship between the measured vibration and the rating score of the unpleasantness revealed that the unpleasantness was in close correlation with the vibration acceleration level (VAL) of the vibration measured. Taking previous results into account, this finding suggests that noise-induced vibrations primarily induce vibratory sensations and through the vibratory sensation or together with some other factors, secondarily contribute to the unpleasantness. The present results suggest that in evaluating high-level low-frequency noise, the effect of vibration should be taken into account.

Key words: Low-frequency noise, Pure tone, High sound pressure level, Body surface vibration, Subjective unpleasantness

Introduction

Low-frequency noise, which is noise in the frequency range below 100 Hz, is prevalently generated in working environments¹⁻⁵. Air-conditioning systems and ventilating systems in buildings generate low- or moderate-level low-frequency noise. Many industrial machines such as air compressors, exhaust fans, large engines, and furnaces generate high-level low-frequency noise, the sound pressure levels of which occasionally exceed 100 dB(SPL).

The loudness of low-frequency noise is not especially high, because the hearing sensitivity of a human being declines at low frequencies⁶. Therefore, low-frequency noise hardly causes adverse physical effects on the auditory organs, such as noise-induced hearing loss. However, it is well known

that low-frequency noise often causes unpleasantness or annoyance⁷. These adverse psychological effects can be induced even by low-level low-frequency noise in living environments^{8,9} and they are expected to be more prevalent in working environments where high-level low-frequency noises are generated¹⁰⁻¹².

Inukai *et al.*¹³ reported that the slopes of the equal-unpleasantness level contours are very similar to those of the equal-loudness level contours. This finding indicates that hearing sensation plays an important role in perceiving unpleasantness or annoyance of persons exposed to low-frequency noise, despite the low audibility of the noise. However, there have been many studies reporting that considering the A-weighted sound pressure level, which is standardized on the basis of the human equal-loudness level contours, is insufficient for evaluating annoyance caused by low-frequency noise or noise with strong low-frequency

*To whom correspondence should be addressed.

content^{11, 12, 14–17}). These studies imply that some other factors, in addition to the loudness, contribute to inducing unpleasantness or annoyance caused by low-frequency noise. In fact, Inukai *et al.*¹⁸) found that human psychological responses to low-frequency noise are primarily based on three factors: sound pressure, vibration, and loudness. This result suggests that not only hearing sensation but also additional factors contribute to unpleasantness or annoyance caused by low-frequency noise and that some of the additional factors may be related to vibration.

When a person is exposed to high-level low-frequency noise, actual body vibration is induced^{19–21}). The levels of this vibration (noise-induced vibration) are not especially high, but we found that noise-induced vibrations measured on the chest or abdomen were closely related to vibratory sensation perceived in each corresponding part of the body²²). Taking the results obtained by Inukai *et al.*¹⁸) into account, it is reasonable to speculate that noise-induced vibrations contribute not only to vibratory sensation but also to unpleasantness or annoyance. If the contribution by noise-induced vibration were confirmed, it would be useful for establishing a more effective evaluation method for adverse psychological effects caused by high-level low-frequency noise in working environments.

The aim of the present study was to clarify the contribution by noise-induced vibrations to subjective unpleasantness of persons exposed to high-level low-frequency noise. To the authors' knowledge, there have been few studies which have investigated the relationship between noise-induced vibration and subjective unpleasantness. To simplify the experimental conditions and to obtain clear results, we used pure tones within a limited frequency range as noise stimuli and measured noise-induced vibrations on the body surface.

Methods

Nine male subjects (21–24 yr, mean = 22.6, SD = 1.0) participated in the experiment. Each subject's hearing ability was confirmed to be normal in the 125- to 8000-Hz range by means of an audiometer (AA-73A, Rion, Japan).

The subject was exposed to low-frequency noise stimuli in a soundproof test chamber with a capacity of approximately 25 m³ (3.16 m (W) × 2.85 m (L) × 2.80 m (H)). The measurements were carried out in winter (a cold and dry season in Japan). The temperature in the test chamber was set at 25°C by an air-conditioning system, and the humidity in the test chamber was maintained at 40% by a humidifier.

Fifteen types of low-frequency noise stimuli (5 frequencies × 3 sound pressure levels) were used. All of the noise stimuli

were stationary pure tones with frequencies of 20, 25, 31.5, 40, and 50 Hz and sound pressure levels of 100, 105, and 110 dB(SPL). No noise stimulus in the frequency range above 50 Hz was used because such frequencies would adversely affect the spatial uniformity of the sound pressure levels in the test chamber²³). To detect noise-induced vibrations that were at higher levels than vibrations inherent in the human body, noise stimuli lower than 20 Hz were not used and the sound pressure levels of the noise stimuli were set to be adequately high. Twelve loudspeakers (TL-1801, Pioneer, Japan), which were installed in the wall in front of the subject, reproduced the noise stimuli in the test chamber. The levels of higher harmonics of the noise stimulus had previously been proved to be sufficiently low when the stimulus was reproduced at levels up to 110 dB(SPL)²³). The background noise in the test chamber (below 30 dB(A)), the dominant part of which originated in the air-conditioning system, was not considered to disturb the experiments because the sound pressure levels of the low-frequency noise stimuli were sufficiently high.

Noise-induced vibrations were measured at four locations on the body surface: the right anterior chest (2 cm above the right nipple), the left anterior chest (2 cm above the left nipple), the right anterior abdomen (5 cm below the pit of the stomach and 5 cm to the right of the midline), and the left anterior abdomen (5 cm below the pit of the stomach and 5 cm to the left of the midline). With a small (3.56 mm × 6.86 mm × 3.56 mm) and lightweight (0.5 g) accelerometer (EGA-125-10D, Entran, USA) attached to each measuring location by double-sided adhesive tape, we detected noise-induced vibration perpendicular to the body surface. The subject wore no clothes on the upper half of the body to allow the accelerometers to be attached. After amplification and low-pass filtering (cut-off frequency = 100 Hz) by a strain amplifier (6M92, NEC San-ei Instruments, Japan), the detected vibration was recorded on DAT (digital audio tape) by a multi-channel data recorder (PC216Ax, Sony Precision Technology, Japan). By using four measuring sets, each of which was composed of the accelerometer and the strain amplifier, we detected the noise-induced vibrations at four locations simultaneously.

The subject, who faced the wall equipped with the loudspeakers, stood in the center of the test chamber. At first, the inherent vibration was recorded (1 min) with no noise stimulus. Then, fifteen types of low-frequency noise stimuli were presented in random order. The duration of each exposure was 1 min when noise-induced vibrations were recorded. The subject was instructed to be relaxed but to keep his upper body erect during exposure to noise

stimulus. After each exposure period, we assigned a rest period (1 min) with no noise stimulus. In each rest period, the subject rated the unpleasantness he had just sensed during the preceding exposure period as either 'not sensed' (rating score = 1), 'mildly sensed' (rating score = 2) or 'strongly sensed' (rating score = 3). This rating scale was the same one as used in our previous study²²⁾ in which we examined the relationship between noise-induced vibration and vibratory sensation. We instructed the subject to define the unpleasantness as a totally unpleasant feeling that included a feeling of discomfort, a feeling of annoyance, a feeling to wish the noise stimulus to diminish, and so on. We also instructed the subject to define the unpleasantness as a feeling that originated not only in hearing sensation but also, if perceived, in other types of sensations. In the instruction, we did not use the word 'vibration'. No reference noise was presented in the rating process for the unpleasantness.

Throughout the measurement session described above, the subject wore no hearing protection so that he could be exposed to low-frequency noise stimuli under normal hearing conditions.

After the measurement session, analysis by means of an FFT analyzer (HP3566A, Hewlett Packard, USA) yielded the power spectrum of the noise-induced vibration detected at each location. Then, the spectral component corresponding to the frequency of the noise stimulus was transformed to a vibration acceleration level (VAL) defined as

$$\text{VAL} = 20 \times \log_{10} (a_{\text{meas}} / a_{\text{ref}}) \text{ [dB]},$$

where a_{meas} is the acceleration measured (m/s^2 (r.m.s.)) and a_{ref} is the reference acceleration equal to 10^{-6} m/s^2 . In this transformation we did not separate the vibration inherent in the human body from the total vibration measured for two reasons: (1) the phase relationship between these two types of vibrations was unknown, and (2) it was considered that the inherent vibration also contributed to unpleasantness.

Statistical analysis was performed by using a statistics software package (SPSS 12.0J for Windows, SPSS Japan, Japan), and a *p*-value less than 0.05 was adopted as the criterion for statistical significance.

The protocol of the present study was approved in advance by the Research Ethics Committee of the National Institute of Industrial Health, Japan, and informed consent was obtained from each subject before the measurements.

Results

Basic characteristics of the measured noise-induced vibration were reported earlier¹⁹⁾. At all the measuring

Fig. 1. Mean rating scores of unpleasantness.

locations and at all the five frequencies, we found that the VAL of noise-induced vibration measured for the noise stimulus at 100 dB(SPL) was higher than the VAL of the inherent vibration. The VALs of the noise-induced vibrations increased in approximately 5-dB increments, which corresponded well with the 5-dB increments in the sound pressure levels of the noise stimuli. We also found that the VALs increased as the frequency of the noise stimulus increased. No clear bilateral asymmetry was found between the VALs measured on the right side of the body and those measured on the left.

In Fig. 1, the mean rating scores of the unpleasantness are shown as a function of the frequency of the noise stimulus. The standard deviations (SD) in the rating score, which are not depicted in the figure, were found to be comparatively large (within the 0.5–1.0 range). This was considered to be chiefly due to the small number of subjects and a rough rating scale for the unpleasantness. On the whole, the unpleasantness tended to be rated more highly at higher sound pressure levels, while the effect of frequency was not remarkable.

We performed categorical principal component analysis on the rating scores of the unpleasantness by limiting the number of principal components to three. Cumulative proportion of variance for the three principal components was found to be larger than 90% (64.8% for the first principal component, 13.6% for the second, and 12.7% for the third), which was considered to be adequately large. Figure 2 shows the relationship between factor loadings of the three principal components and fifteen types of the low-frequency noise stimuli. The factor loading of the first principal component, which was a dominant component, was very large, regardless of the type of noise stimulus. In the present study we used the low-frequency noise stimuli within a limited range of

Fig. 2. Relationship between factor loadings of the principal components and the low-frequency noise stimuli.

high sound pressure levels (100–110 dB(SPL)). Hence, it is reasonable to speculate that the first principal component corresponded to the effect of the high sound pressure levels of the noise stimuli. This dominant effect of the first principal component was supposed to be the chief reason why we observed no clear effect of frequency in the ratings of the unpleasantness. The factor loading of the third principal component tended to increase with frequency and sound pressure level of the noise stimulus. It was considered plausible that the third principal component corresponded to the effect of hearing sensation. A similar tendency was also observed for the second principal component, but the tendency of the second principal component was less remarkable than that of the third component and therefore, we could not conclusively relate the second principal component to any specific effect. However, taking into consideration the three factors (sound pressure, vibration, and loudness) found by Inukai *et al.*¹⁸⁾, we speculate that the second principal component corresponded to the effect of vibration.

The VAL of the noise-induced vibration measured in the present study is considered to be a representative value of the vibration sensation. Figure 3 (a) shows the correlation between the mean rating scores of the unpleasantness and the mean VALs of the noise-induced vibration measured at the chest. The correlations obtained at the abdomen are shown in Fig. 3 (b). In these figures two VALs, which were measured at the right and left sides of the body, are plotted to one rating score, because no clear bilateral asymmetry was observed in the VALs. The solid line in the figure is a regression line calculated on the basis of the relationship between the mean ratings and the mean VALs, regardless of the frequency of the noise stimulus.

In Table 1, the correlation coefficients calculated in the

Fig. 3. Frequency-independent correlations between the mean rating score (RS) of unpleasantness and the mean VAL of the noise-induced vibration measured (a) at the chest, and (b) at the abdomen.

Table 1. Correlation coefficients obtained in the present and previous studies

	Correlation coefficients	
	Chest	Abdomen
VAL vs. unpleasantness	0.711 **	0.794 **
VAL vs. vibratory sensation	0.841 **	0.930 **

**: $p < 0.01$. In the present study the VALs of noise-induced vibrations were correlated with the ratings of unpleasantness, while in the previous study they were correlated with the ratings of vibratory sensation perceived in the corresponding part of the body.

present study (for unpleasantness) are listed together with those calculated in our previous study (for vibratory sensation). It should be noted that in the present study, the ratings of the unpleasantness were commonly correlated with the VALs measured at two locations (the chest and the abdomen), because the unpleasantness was rated once for every noise stimulus. In our previous study²²⁾, in contrast, the VALs measured at the chest were correlated with the ratings of vibration perceived in the chest and, the VALs measured at the abdomen were correlated with the ratings

Fig. 4. Estimation of the 'best-fit' frequency-weighting for the correlation between the ratings of unpleasantness and the VALs measured (a) at the chest, and (b) at the abdomen.

of vibration perceived in the abdomen. The frequency-independent correlations in the present study were found to be statistically significant. At both locations, the correlation coefficient obtained for the unpleasantness was smaller than that obtained for the vibratory sensation.

In general, a psychological response such as unpleasantness is frequency-dependently related to a physical stimulus such as vibration. We roughly estimated a 'best-fit' frequency-weighting for the VAL, hypothesizing that the slope of the 'best-fit' frequency-weighting was constant in the 20- to 50-Hz range. The 'best-fit' slope was determined by optimizing the correlation coefficient while the slope was varied between -20 and $+20$ dB/oct. in 0.5 -dB/oct. steps. In this estimation we temporarily set the correction at 50 Hz to be 0 dB. In assessing a slope of -6.0 dB/oct., for example, corrections for the VALs were $+8.0$ dB at 20 Hz, $+6.0$ dB at 25 Hz, $+4.0$ dB at 31.5 Hz, $+2.0$ dB at 40 Hz, and 0.0 dB at 50 Hz. As illustrated in Fig. 4, the maximum appeared in the trace of the correlation coefficient at both locations (the chest and the abdomen), indicating that the 'best-fit' frequency-weighting had been estimated without ambiguity. The estimated slopes of the 'best-fit' frequency-

Table 2. Correlation coefficients between the mean rating score of unpleasantness and the mean VAL, the mean 'best-fit' frequency-weighted VAL (VAL_w), the sound pressure level (SPL), the A-weighted sound pressure level (SPL_A), and the 'best-fit' frequency-weighted sound pressure level (SPL_w)

	Correlation coefficients	
	Chest	Abdomen
VAL	0.711 **	0.794 **
VAL_w	0.841 **	0.822 **
SPL	0.789 **	
SPL_A	0.665 **	
SPL_w	0.850 **	

**: $p < 0.01$.

weightings were negative at both locations: -8.5 dB/oct. at the chest and -3.0 dB/oct. at the abdomen. The difference between the 'best-fit' slopes estimated at the two locations was considered to be due to differences between the mechanical characteristics (frequency-characteristics in particular) of the noise-induced vibrations at these two locations¹⁹⁾. It should be noted that the frequency-dependence of the VAL decreases when applying a frequency-weighting with a negative slope. Therefore, negative slopes of the 'best-fit' frequency-weightings were not contradictory to the assumption that the second principal component in Fig. 2 corresponded to the effect of vibration. The mean rating scores of the unpleasantness were correlated with the mean VAL_w values of noise-induced vibrations measured at the chest and abdomen. In this paper, VAL_w represents the VAL to which the 'best-fit' frequency-weighting was applied. In Table 2, the correlation coefficients for the correlations with VAL_w values are listed together with those for the correlations with VALs to which no frequency-weighting was applied.

For comparison, in Fig. 5, the mean rating scores of the unpleasantness are correlated with the sound pressure levels and the A-weighted sound pressure levels of the low-frequency noise stimuli. The A-weighted sound pressure level is considered to be a representative value of the loudness sensation. The correlation coefficients for these correlations, both of which were found to be statistically significant, are also listed in Table 2. The correlation coefficient calculated for the sound pressure level (0.789) was comparable to that calculated for the VAL measured at the abdomen (0.794), while the correlation coefficient calculated for the A-weighted sound pressure level (0.665) was slightly smaller than that calculated for the VALs measured at the chest (0.711).

The 'best-fit' frequency-weighting for the sound pressure

Fig. 5. Correlations between the mean rating score (RS) of unpleasantness and (a) the sound pressure level, and (b) the A-weighted sound pressure level of the low-frequency noise stimulus.

level was also estimated by the same method as described before. As a result, the 'best-fit' slope for the sound pressure level was determined to be +3.5 dB/oct. It should be noted that the estimated 'best-fit' slope (+3.5 dB/oct.) was positive and clearly gentler than the slope of the A-weighting characteristic (approximately +14 dB/oct. in the 25- to 50-Hz range). This disagreement was consistent with many previous studies which have reported that the A-weighted sound pressure level is insufficient for evaluating low-frequency noise^{11, 12, 14-17}. The correlation coefficient calculated for the 'best-fit' frequency-weighted sound pressure level (SPL_w) is also listed in Table 2.

Discussion

The VAL of noise-induced vibration increased with the sound pressure level of the low-frequency noise stimulus¹⁹. On the other hand, the rating of the unpleasantness also increased with the sound pressure level (Fig. 1). It is therefore quite natural that the VALs closely correlated with the ratings of unpleasantness. As shown in Table 2, however, the correlation coefficients between the ratings of unpleasantness and VALs (0.711 at the chest and 0.794 at the abdomen)

were comparable to or larger than the correlation coefficient for the correlation with the A-weighted sound pressure levels (0.665). The loudness of noise definitely contributes to subjective unpleasantness and, the A-weighted sound pressure level is a representative value of the loudness. Hence, comparable or larger correlation coefficients calculated for the VALs suggest that the vibrations induced in the trunk of the body (the chest and the abdomen) really do contribute to the unpleasantness.

In our previous study²² we found that the VALs of noise-induced vibration significantly correlated with the ratings of vibratory sensation perceived in each corresponding part of the body. Vibratory sensation is considered to be induced chiefly by a vibration stimulus such as noise-induced vibration, while the unpleasantness defined in the present study is a total sensation caused by a variety of stimuli and sensations that include noise-induced vibration and vibratory sensation. It is therefore reasonable to hypothesize that noise-induced vibration is related primarily to the perception of vibration and through the vibratory sensation or together with other stimulating factors, contributes to inducing unpleasantness as a secondary effect.

Comparison of the correlation coefficients obtained in the present and previous studies indicate that the VALs of noise-induced vibrations measured at both locations (the chest and the abdomen) were in closer correlation with the ratings of the vibratory sensation perceived in each corresponding part of the body than with the ratings of the unpleasantness (Table 1). This supports the hypothesis that noise-induced vibration is related primarily to the perception of vibration and through the vibratory sensation, contributes to inducing unpleasantness as a secondary effect.

The slopes of the 'best-fit' frequency-weightings for the VALs were estimated to be -8.5 dB/oct. at the chest and -3.0 dB/oct. at the abdomen, respectively. The mean value (-5.8 dB/oct.) of these two slopes is very similar to the slope of the W_k -weighting curve (approximately -6 dB/oct. in the 20- to 50-Hz range). The W_k -weighting²⁴ is a frequency-weighting characteristic which is standardized to evaluate discomfort of a recumbent person exposed to vertical whole-body vibration. In applying the W_k -weighting, it is assumed that the recumbent person is excited through the posterior surface of the trunk of the body (the posterior chest and abdomen). The human body is excited only vertically by vertical whole-body vibration, while noise-induced vibration is considered to be approximately isotropic, because the wavelength of low-frequency noise (approximately 6.8 m at 50 Hz) is longer than the height of a human being. The mechanical characteristics of noise-induced vibration are

different from those of vertical whole-body vibration and hence, the mechanisms to perceive noise-induced vibration may be different from those which perceive vertical whole-body vibration. Thus, the similarity between the slope of the W_k -weighting and that of the 'best-fit' frequency-weighting estimated in the present study does not incontrovertibly support the contribution by noise-induced vibration to inducing unpleasantness. However, the similarity is not contradictory to the hypothesis that the perception of noise-induced vibration in the trunk of the body plays an important role in evoking unpleasant feelings in a person exposed to high-level low-frequency noise.

According to Inukai *et al.*¹⁸⁾, three factors (sound pressure, vibration, and loudness) contribute to a person's subjective impressions of low-frequency noise. The sound pressure level is reasonably considered to be a representative value of the sound pressure sensation, while the VAL of noise-induced vibration and the A-weighted sound pressure level are considered to be representative values of the vibration sensation and the loudness sensation, respectively. All of these three representative values were found to significantly correlate with the ratings of unpleasantness and the correlation coefficient calculated for the sound pressure level was comparable to or larger than those for the VAL of the noise-induced vibration and those for the A-weighted sound pressure level (Table 2). We believe that the contribution by the sound pressure level to the unpleasantness naturally involves not only the contribution by the sound pressure but also the contributions by the other two factors (vibration and loudness), because both the VAL of the noise-induced vibration and the A-weighted sound pressure level increase with the sound pressure level of the low-frequency noise stimulus. In contrast, the VAL is not related to the loudness and, the A-weighted sound pressure level is not related to the vibration. This may be one of the reasons why the ratings of unpleasantness were, on the whole, most closely correlated with the sound pressure level. It is an intrinsic characteristic of low-frequency noise that the three factors (sound pressure, vibration, and loudness) stimulate a person simultaneously. Hence, it is difficult to discriminate the contribution by one factor from the total contribution by the three factors to subjective unpleasantness. To clarify the relative importance of the three factors, future studies are needed.

The slope of the 'best-fit' frequency-weighting for the sound pressure level (+3.5 dB/oct.) was estimated to be clearly gentler than the slope of the A-weighting characteristic. This indicates that noise content at lower frequencies should be given more importance in evaluating high-level low-frequency noise. Inukai *et al.*²⁵⁾ previously

proposed the LF-weighting characteristic for evaluating low-frequency noise. They modified the low-frequency part of the A-weighting characteristic by taking into consideration not only the effect of hearing sensation but also the effects of vibratory and oppressive sensations. As a result, the LF-weighting characteristic was established as a frequency-weighting characteristic by applying which noise at frequencies below 500 Hz could be more effectively evaluated. Our present results suggest that noise-induced vibrations are, through vibratory sensation or together with other factors, related to subjective unpleasantness. By taking into account the effect of noise-induced vibration, an evaluation method for high-level low-frequency noise may possibly be established in the future.

At low or moderate sound pressure levels, however, the VALs of noise-induced vibrations are expected to be lower than those of vibrations inherent in the human body. In addition, at sufficiently low or high frequencies, the VALs of noise-induced vibrations are expected to decrease due to the mechanical characteristics of the human body in response to airborne vibration. In such conditions, the contribution by noise-induced vibration to inducing unpleasantness is considered to decrease or disappear. To utilize noise-induced vibration for establishing a new evaluation method for high-level low-frequency noise, it is needed to verify effective ranges of frequency and sound pressure levels in which noise-induced vibration contributes to inducing subjective unpleasantness.

Conclusions

It was found that the ratings of subjective unpleasantness were significantly correlated with the VALs of the noise-induced vibration measured on the body surface. Taking previous results into account, we suggest that noise-induced vibrations primarily induce vibratory sensation and through the vibratory sensation or together with some other stimulating factors, they secondarily contribute to inducing unpleasantness. To sufficiently evaluate unpleasantness or annoyance caused by high-level low-frequency noise, the effect of vibration should be taken into account. The present study was carried out using low-frequency noise stimuli within a limited range of frequency and sound pressure level. In addition, the number of subjects was small and a rough rating scale for subjective unpleasantness was used. Thus, in order to confirm the present results, more detailed studies need to be conducted in the future.

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