Some characteristics of human body surface vibration induced by low frequency noise

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The body surface vibration induced by low frequency noise (noise-induced vibration) was measured at the forehead, the anterior chest and the anterior abdomen. At all the measuring locations, the increase steps in the vibration acceleration levels of the noise-induced vibrations was in good agreement with the increase steps, in the sound pressure levels of the noise stimuli. The vibration acceleration level measured at the forehead was found to increase suddenly at around 31.5-40 Hz, while the acceleration levels measured at the chest and abdomen increased with frequency at approximately constant rates in the 20- to 50-Hz range. Our results showed no clear evidence of the effect of posture or bilateral asymmetry in the noise-induced vibration. We found that the noise-induced vibrations measured at the chest and abdomen were correlated negatively with the body fat percentage.

Key words: *Low frequency noise, Human body vibration, Body surface, Vibration acceleration level, Linear system, Posture, Bilateral asymmetry, Physical constitution of the human body*

Introduction

Low frequency noise, that is, noise below 100 Hz, is widely generated in living and working environments [1]. One of the typical sources of low frequency noise in the living environment is built-in air-conditioning system in a house, which generates low-level but continuous low frequency noise. In the working environment, on the other hand, various machines such as blowers, exhaust fans, air compressors and the like generate high-level low frequency noise, the sound pressure level of which occasionally exceeds 100 dB (SPL).

Mechanical vibration is induced in the human body when a person is exposed to high-level low frequency noise [2, 3]. The level of this vibration (noise-induced vibration) is not especially high, but many previous studies suggest that noise-induced vibration plays an important role in the human psychological and perceptual responses to low frequency noise. For example, Yamada et al. reported that deaf persons perceived low frequency noise through sensing vibration in the chest [4]. Takahashi et al. showed that subjective ratings of vibratory sensation perceived in the chest and abdomen were closely correlated with the vibration induced at each corresponding location [5].

Recent studies by Castelo Branco et al. suggest that noise-induced vibration is associated with adverse health effects caused by low frequency noise [6-8]. They examined workers who had been exposed to high-level low frequency noise for more than 10 years and found some pathological changes in the workers' bodies, such as pericardial thickening, pulmonary fibrosis and so on. They called the pathological changes 'vibroacoustic disease' and presumed that long-term exposure to the noise-induced vibration was one of the causes. Many pathological changes were found in the chest, which is where researchers would expect noise-induced vibration to be induced at a comparatively high level [2, 3]. Clarifying the characteristics of noise-induced vibration should be helpful to clinicians attempting to assess low frequency noise from a medical viewpoint.

In our previous study we measured noise-induced vibration at the chest and abdomen of sitting subjects [2]. We found that the vibration acceleration levels of the noise-induced vibration measured at the chest were higher than those measured at the abdomen. We also found that the increase steps in the noise-induced vibration were in good agreement with the increase steps in the sound pressure levels of the noise stimuli. However, we wanted to make more precise measurements, because the previous results were obtained under experimental conditions with too many variables, such as a wide range of the subject's age (24-57 yr).

The aim of the present study was to clarify the detailed characteristics of noise-induced vibration. We limited the subjects' age to fall within a narrow range and carried out the measurements in a test chamber where temperature and humidity were controlled. The forehead was newly included in the measuring locations, in addition to the chest and abdomen. We measured the noise-induced vibration not only with subjects sitting but also with them standing, which allowed us to examine characteristics such as position-dependence, effects of subject's posture, bilateral asymmetry, effects of the subject's physical constitution etc.

Subjects

Nine subjects participated in the measurements; All of the subjects were healthy male students, and their ages ranged from 21 to 24 yrs (mean = 22.6, SD = 1.0). Their height and weight were 173.0 ± 3.5 cm and 65.8 ± 4.5 kg (mean ± SD), respectively.

This study was approved by the ethics committee of the National Institute of Industrial Health, and informed consent was obtained from each subject before the measurement.

Measurement methods

The methods for measuring noise-induced vibration, which are briefly described in the following paragraphs, were almost the same as the methods used in our previous study [2]. The measurements were carried out in a test chamber with a capacity of about 25 m^3 [9] in winter (a dry season in Japan). The temperature in the test chamber was initially set at 25℃ and, if the subject complained of discomfort, it was adjusted within the 23-27℃ range. The humidity in the test chamber was kept at 40% by a humidifier.

Fifteen kinds of low frequency noise stimuli (5 frequencies x 3 sound pressure levels) were used. All of them were pure tones; we used 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 higher than 50 Hz was used, because the spatial uniformity of the sound pressure levels in the test chamber would deteriorate above 50 Hz [9]. To detect only those noise-induced vibrations which were higher in level than those inherent in the human body, we avoided using noise stimuli lower than 20 Hz and the sound pressure levels of the noise stimuli were set to be sufficiently high. A function generator (HP3314A, Hewlett Packard, USA) generated sinusoidal signals as the source of the noise stimuli. The signals were amplified by power amplifiers (PC4002M, Yamaha, Japan) and then reproduced by 12 loudspeakers (TL-1801, Pioneer, Japan) installed in the wall in front of the subject (Fig. 1). The levels of the higher harmonics of the noise stimuli had proved adequately low when the

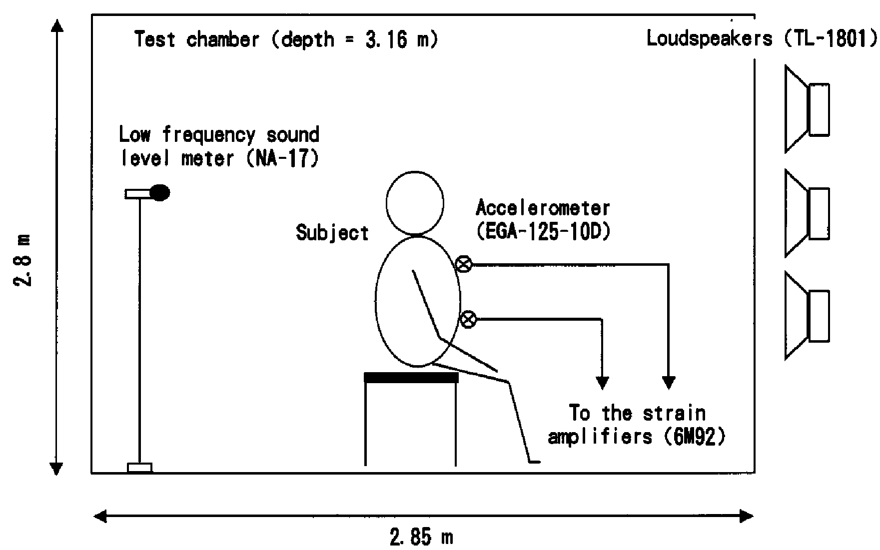


Figure 1. The experimental apparatus in the test chamber. The subject sat on a stool at the centre of the test chamber stood at the same place after removing the stool.

stimuli were reproduced at levels of 110 dB or less [9] . The sound pressure level was adjusted so that the desired level could be measured at the centre of the test chamber, at 100 cm height (corresponding to the position of the sitting subject's chest) or at 120 cm height (corresponding to the position of the standing subject's abdomen), without a subject present.

Noise-induced vibrations were measured at 5 measuring locations on the body surface: at the forehead (2 cm above the level of the eyebrow, and on the midline), 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). When an accelerometer is attached on the body surface, the accelerometer and the local tissue around it may form an additive local mechanical system and result in a difference between the accelerometer measurement and the acceleration of the body surface. To minimize this change around each measuring location, it is necessary to use an accelerometer which is as small and lightweight as possible [10]. Hence, we used a small (3.56 mm x 6.86 mm x 3.56 mm) and lightweight (0.5 g) accelerometer (EGA-126-l0D, Entran, USA) as a vibration detector. The accelerometer, which was attached at each measuring location with double-sided adhesive tape and no other supporting material, detected noise-induced vibration perpendicular to the body surface. After being amplified by a strain amplifier (6M92, NEC San-ei Instruments, Japan), the detected vibration was recorded on DAT with a multi-channel data recorder (PC216Ax, Sony Precision Technology, Japan). Simultaneous measurements at 5 measuring locations were performed with 5 identical measuring sets, each of which consisted of an accelerometer and a strain amplifier.

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

$$\text{Vibration acceleration level (VAL)} = 20x\log 10(a_{meas}/a_{ref}),$$

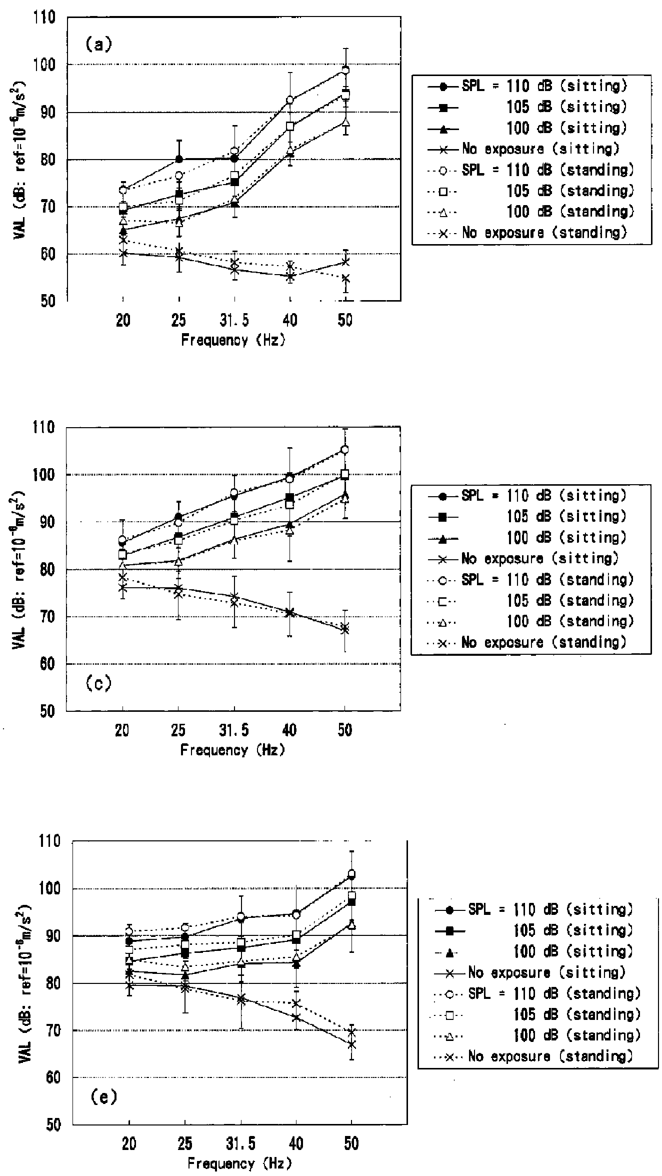
where a_{meas} was a measured acceleration (m/s^2(r.m.s.)) and a_{ref} was the reference acceleration equal to 10-6 m/s2 [11]. In this transformation, we did not separate the inherent vibration from the total vibration, because the phase relationship between the inherent vibration and the noise-induced vibration was unknown. It should be noted that in this paper, the VALs of the measured noise-induced vibration were probably contaminated by those of the inherent vibration and that the degree of contamination was more significant at lower frequencies [2].

Each measurement consisted of two sessions. In the first session the subject sat on a stool at the centre of the test chamber (Fig. 1), and in the second session he stood at the same place without any supporting instruments. At the beginning of each session, the inherent body surface vibration with no noise stimulus was recorded (1 min). Next, a rest period with no noise stimulus (1 min) and an exposure period with a noise stimulus (1 min) when the noise-induced vibrations were recorded were continued alternately. The subject, who wore no clothes on the upper half of the body to allow the accelerometers to be attached, was instructed to keep his upper body erect during an exposure period. Fifteen kinds of noise stimuli were presented in random order for every subject and every session.

We used a statistics software package (SPSS for Windows 10.0J, SPSS Japan, Japan) to evaluate the effect of the subject's posture, bilateral asymmetry and physical constitution. In the statistical analysis of the effect of posture, we used ANOVA to examine the statistical significance of the difference between the noise-induced vibrations for the sitting subjects and those for the standing subjects. We also used ANOVA to examine the bilateral asymmetry between the noise-induced vibrations measured at bilaterally symmetrical measuring locations. To determine the effect of the subject's physical constitution, we used the statistics package to calculate Pearson's correlation coefficients between the VALs of the noise-induced vibration and the subject's body fat percentage, which was estimated by a body-fat meter (TBF-501, Tanita, Japan).

Results

Figure 2 shows the VALs of the noise-induced vibration (means ± SD) measured at five measuring locations, together with the VALs of the inherent vibration. Solid lines in the figure represent the VALs for the sitting subjects and dotted lines represent those for the standing subjects. For simplicity, only the upward SDs are



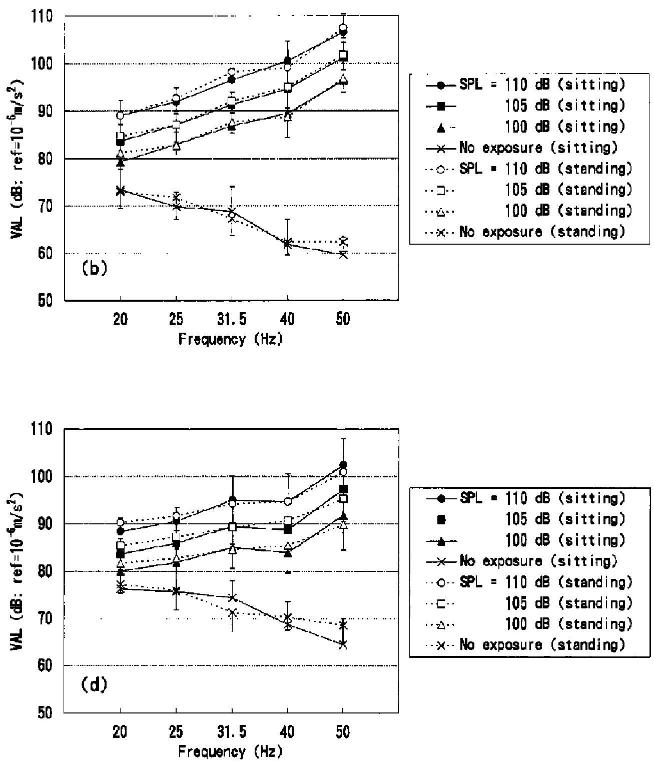


Figure 2. The vibration acceleration level (VAL) measured (a) at the forehead, (b) at the right chest, (c) at the left chest, (d) at the right abdomen and (e) at the left abdomen. Solid lines represent the VALs for the sitting subjects, and dotted lines represent those for the standing subjects.

shown for the sitting subjects and only the downward SDs are shown for the standing subjects. At all the measuring locations, the VALs of the noise-induced vibration increased with the frequency and sound pressure level of the noise stimulus, while the VALs of the inherent vibration decreased as the frequency of the noise stimulus increased. This is because the inherent vibration originating in vital activities such as the heartbeat is distributed mainly in the lower frequency range. The highest VAL of the noise-induced vibration (about 107 dB with 50 Hz, 110 dB noise stimulus) was measured at the chest. The noise-induced vibrations measured at the abdomen were at slightly lower levels than those measured at the chest, and the noise-induced vibrations measured at the forehead were at clearly lower levels. At all the measuring locations, the increase step in the VALs of the noise-induced vibrations was found to be about 5dB, which was in good agreement with the increase step (5dB(SPL)) in the sound pressure levels of the noise stimuli.

The VALs of the noise-induced vibration measured at the chest were found to increase with frequency at an approximately constant rate. A similar tendency was found in the noise-induced vibration measured at the abdomen. At the forehead, in contrast with the other measuring locations, the VALs of the noise-induced vibration were very low at lower frequencies (20-25 Hz), but they rose suddenly around 31.5-40 Hz (Fig. 2(a)). As a result, the highest rate of increase with frequency in the 20- to 50-Hz range was measured at the forehead.

Table I summarizes the statistical significance of the difference between the VALs for the sitting subjects and those for the standing subjects. The effect of posture was not statistically significant at any of the measuring locations.

Measuring locations		p-values
	Head	0.912
Chest	Right	0.308
	Left	0.508
Abdomen	Right	0.569
	Left	0.058

Table 1. Statistical significance of the difference between the vibration acceleration levels for the sitting subject and those for the standing subject. No significant difference was found.

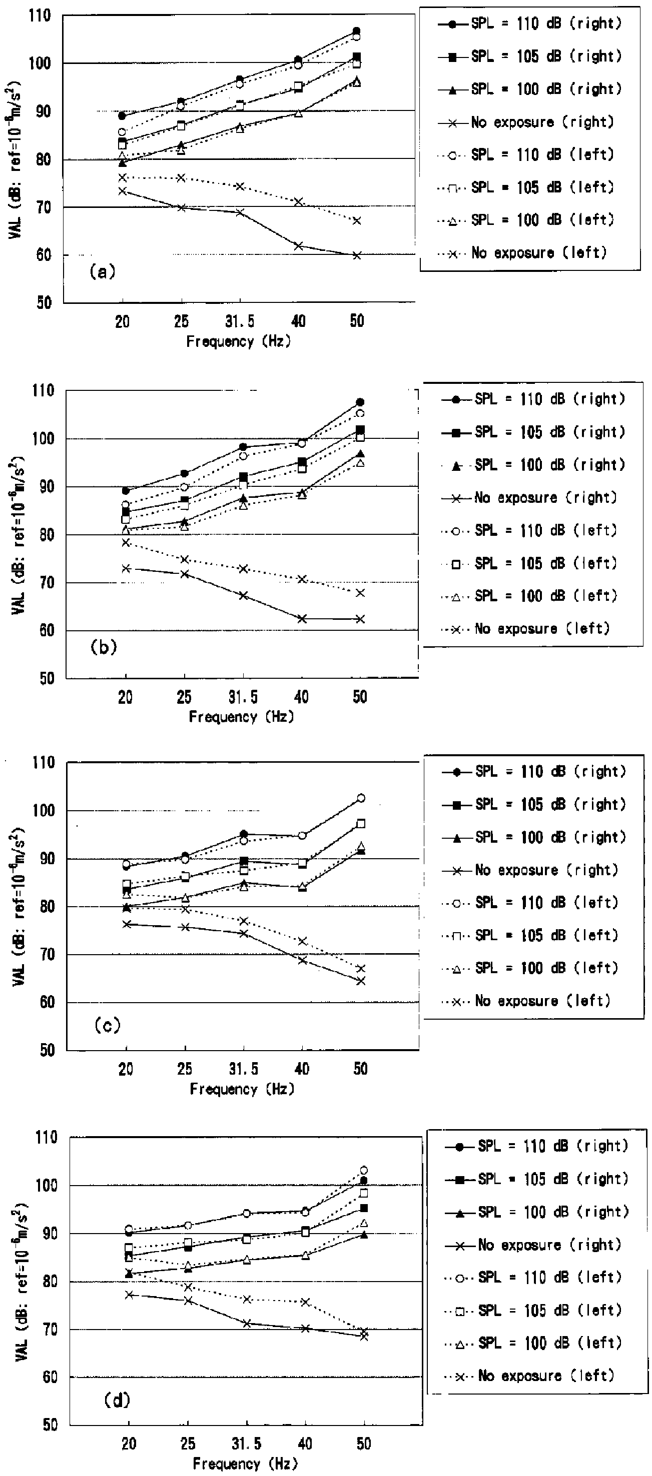


Figure 3. Comparison of the vibration acceleration level (VAL) measured (a) at the chest of the sitting subject, (b) at the chest of the standing subject, (c) at the abdomen of the sitting subject and (d) at the abdomen of the standing subject. Solid lines represent the VALs measured on the right side of the body, and dotted lines represent those measured on the left side of the body.

Table II. Statistical significance of the difference between the vibration acceleration levels measured at the bilaterally symmetrical locations. (**) represents a significant difference at the level of $p < 0.01$ (two- sided).

Measuring locations	p-values For sitting subjects	p-values For standing subjects
Chest	0.174	0.003**
Abdomen	0.883	0.120

Table III. Pearson's correlation coefficients between the vibration acceleration levels and the body fat percentage. (*) represents a significant difference at the level of $p < 0.05$ (two-sided) and (**) at the level of $p < 0.01$ (two-sided). The blank cell in the table represents no significance.

Noise stimuli		Pearson's correlation coefficients			
		Chest		Abdomen	
Frequency (Hz)	SPL(dB)	Right	Left	Right	Left
	100	-	-	-0.731 (p=0.025)*	-
20	105	-	-	-0.702 (p=0.035)*	-
	110	-0.711 (p=0.032)	-	-0.714 (p=0.031)*	-
	100	-	-	-	-
25	105	-	-	-	-
	110	-	-	-	-
	100	-	-	-	-
31.5	105	-	-	-	-
	110	-	-	-	-
	100	-	-	-0.735 (p=0.024)*	-
40	105	-	-	-0.784 (p=0.012)*	-
	110	-	-	-0.716 (p=0.030)*	-
	100	-0.797 (p=0.010)*	-0.786 (p=0.012)*	-	-0.726 (p=0.027)*
50	105	-0.871 (p=0.002)*	-0.741 (p=0.022)*	-	-0.808 (p=0.008)**
	110	-0.864 (p=0.003)*	-0.762 (p=0.017)*	-	-0.671 (p=0.048)*

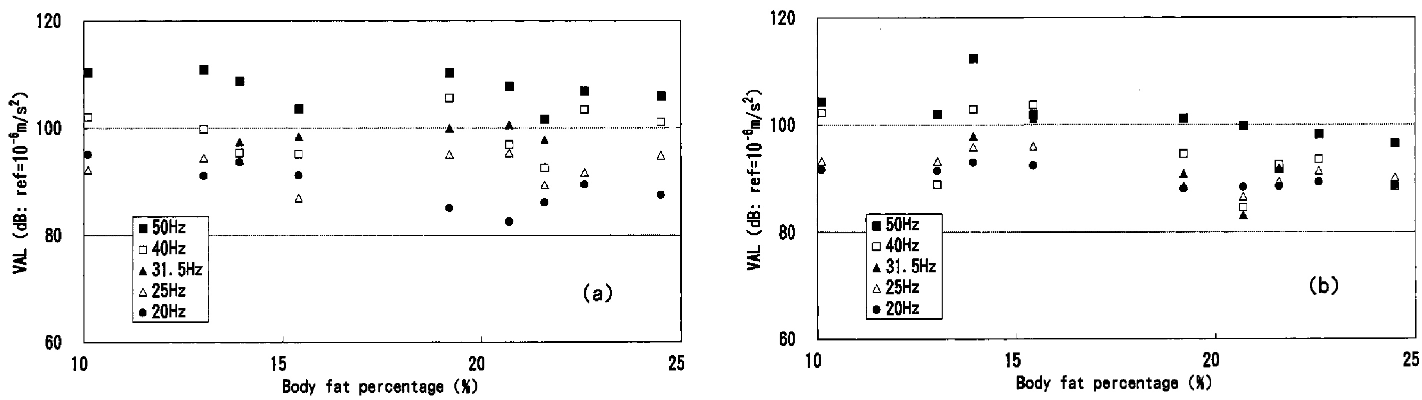


Figure 4. The correlation between the body fat percentage and the vibration acceleration levels (VAL) measured (a) at the right chest of the standing subject and (b) at the right abdomen of the standing subject. The sound pressure levels of the noise stimuli are 110 dB(SPL) in all cases.

Figure 3 compares the VALs of the noise-induced vibrations measured at bilaterally symmetrical measuring locations. Solid lines in the figure represent the VAL measured on the right side of the body, and dotted lines represent those measured on the left side of the body. As seen in Table II, significant bilateral asymmetry was found at the chest of standing subjects ($p = 0.003$); however, no statistically significant difference was found at the other measuring locations.

Figure 4 shows examples of the correlation between the VAL of the noise-induced vibration and the body

Table IV. Pearson's correlation coefficients between the vibration acceleration levels and the body fat percentage. (*) represents a significant difference at the level of p < 0.05 (two-sided) and (**) at the level of p < 0.01 (two-sided). The blank cell in the table represents no significance.

Noise stimuli		Pearson's correlation coefficients			
		Chest		Abdomen	
Frequency (Hz)	SPL(dB)	Right	Left	Right	Left
	100	-0.837 (p=0.005)**	-	-	-
20	105	-0.776 (p=0.014)*	-	-0.833 (p=0.005)**	-
	110	-0.755 (p=0.019)*	-	-0.811 (p=0.008)**	-
	100	-	-	-	-
25	105	-	-	-0.678 (p=0.045)*	-
	110	-	-	-	-
	100	-	-	-	-
31.5	105	-	-	-	-
	110	-	-	-	-
	100	-	-	-	-
40	105	-	-	-0.758 (p=0.018)*	-
	110	-	-	-	-
	100	-	-0.762 (p=0.017)*	-	-0.739 (p=0.023)*
50	105	-	-0.731 (p=0.025)*	-	-0.761 (p=0.017)*
	110	-	-0.757 (p=0.018)*	-0.706 (p=0.034)*	-0.795 (p=0.011)*

fat percentage. Tables III and IV summarize the Pearson's correlation coefficients and the statistical significance of the correlation. The VALs of the noise-induced vibrations measured at the chest and abdomen, as a whole, tended to correlate negatively with the body fat percentage. At the forehead, on the other hand, no significant correlation was verified for any of the noise stimuli.

Discussion

In this study we measured noise-induced vibration at the forehead, the chest and the abdomen. At all the measuring locations, the increase step in the VALs of the noise-induced vibration corresponded well to the increase step in the sound pressure levels of the low frequency noise stimuli (Fig. 2). This linear response to the noise stimuli is consistent with our previous results [2]. In general, the wavelength of low frequency noise is sufficiently longer than the size of a human being. For example, provided that the sound velocity in the atmosphere is 340 m/s, the wavelength of the noise with a frequency of 50 Hz or less is 6.8 m or more. Hence, for a human being, exposure to low frequency noise with frequencies below 50 Hz is similar to periodic fluctuation in the atmospheric pressure, and it is reasonable to hypothesize that noise-induced vibration is isotropic and generated mainly by the difference in the atmospheric pressures between the inside and the outside of the body. Because this pressure difference is considered to change approximately in proportion to the sound pressure level of the low frequency noise stimulus, the linear response of the noise-induced vibration can be elucidated by the above hypothesis. Thus, in the limited range of frequency and sound pressure level, the human body is considered to be a mechanical system that responds linearly to airborne vibrating stimuli such as low frequency noise.

The bilateral asymmetry in the noise-induced vibration was found to be statistically significant only at the chest of the standing subject (Table II), with higher-level noise-induced vibration measured at the right chest. Wodicka et al. introduced sound stimuli from the mouth to the lung and measured the chest wall vibration [12, 13]. They found that the right chest wall was excited at higher levels than the left chest wall and presumed that this was due to the bilateral asymmetry in the anatomical structures in the human body. They used broadband sound stimuli with frequencies higher than 100 Hz and vibrated the intrathoracic structures. In our study, on the other hand, we used pure tonal stimuli in the 20- to 50-Hz range and vibrated the whole body from the atmosphere. Nevertheless, the chest wall vibrations measured in both studies were generated by an essentially identical source, which is the pressure difference between the inside and the outside of the body. Therefore, it is possible that the low frequency noise stimuli induced the bilaterally asymmetrical vibration in the chest in both cases. The anatomical structures in the abdomen are also organized to be bilaterally asymmetrical, which implies that the abdominal vibration would also be bilaterally asymmetrical, but we could not verify a statistically significant bilateral asymmetry in the noise-induced vibration at the abdomen. Wodicka et al. used noise stimuli in a frequency range higher and wider than ours. Further studies using noise stimuli in a wider range of frequency are needed to verify the bilateral asymmetry in the noise-induced vibration.

The mechanical characteristics of the anatomical structures in a sitting person are different from those in a standing person. For example, the intraabdominal pressure in the body part around the hips is presumed to be at a higher level for a sitting person than for a standing person. The change in the intraabdominal pressure causes a change in the pressure difference between the inside and the outside of the body. which may result in a change in the magnitude of the noise-induced vibration. In this study, however, the effect of posture on the noise-induced vibration was not statistically significant (Table I). We speculate that this is due to the fact that the anatomical structures around the five measuring locations, none of which were proximal to the lower trunk, hardly changed their mechanical characteristics when the subject changed his posture. To verify the effect of posture on the noise-induced vibration, one needs to measure the body surface vibration at the lower abdomen or the lower back.

We found that the VALs of the noise-induced vibrations measured at the chest and abdomen tended to correlate negatively with the body fat percentage (Tables III and IV). This is consistent with our previous results that the magnitude of the noise-induced vibration measured at the abdomen was correlated negatively with BMI (Body Mass Index) [2]. An increase in the body fat results in thickening the body tissue under the skin and changes in the mechanical characteristics of the body tissue, including a reduction of stiffness in the body tissue. These changes in the body tissue interfere with the propagation of vibration in the human body and result in the negative correlation we found. The VAL of the noise-induced vibration measured at the forehead showed no significant correlation with the body fat percentage. We believe the vibration induced at the forehead is less influenced by the change in the mechanical characteristics of the body tissue than the vibrations induced at the chest and abdomen because the body tissue under the skin at the forehead is scarcer than that under the skin at the chest and abdomen. This may be speculated to be a reason why we could find neither negative nor positive significant correlation between the vibration induced at the forehead and the body fat percentage.

One new finding in this study was that the VAL of the noise-induced vibration measured at the forehead increased steeply around 31.5-40 Hz, in contrast with approximately constant rates of increase with frequency found at the chest and abdomen. Kobayashi et al. vibrated the human head using a vibrating table and found that the vibration transmissibility in the human head had a resonance-like peak around 50-80 Hz [14]. In our study, on the other hand, the human head was vibrated by high-level low frequency noise stimuli with frequencies below 50 Hz. In spite of the different vibrating methods, the results of both studies correspond well qualitatively in the frequency range just below 50 Hz. Because the body tissue between the skin at the forehead and the skull is scarce, the characteristics of the skull may dominate over the characteristics of the vibration induced at the forehead. Some resonance frequencies of the skull were found in the frequency range around 1 kHz or higher [15, 16] but, to the authors' knowledge, they were not measured in the frequency range below 100 Hz. Although we have not drawn a specific conclusion because of the small amount of available experimental data, we believe resonance-like vibration may be induced in the human head at frequencies around 50 Hz by airborne vibrating stimuli such as high-level low frequency noise.

In this study we failed to sufficiently control some of the experimental conditions. For example, only male subjects participated, and the measurements were conducted under limited experimental conditions, such as using a narrow range of frequency and a narrow range of sound pressure level. Hence, many characteristics of the human body surface vibration remain unknown. In addition, we still do not know how the body surface vibration is related to the vibration induced in the inner body, which needs to be investigated for assessing low frequency noise from a medical viewpoint. Future studies of noise-induced vibration should be conducted under more various experimental conditions, with an additional goal of establishing the relationship between the body surface vibration and the vibration induced in the inner body.

Acknowledgments

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noise notes

Regional jets preferred

The regional jets that dominate air traffic at Northwest Arkansas Regional Airport create less noise for surrounding neighbors than bigger planes, consultants have told airport officials. Ryk Dunkelberg of Barnard Dunkelberg & Co., in Tulsa and Ron Reeves of Mestre Greve Associates in Newport Beach, Calif., provided encouraging news to airport officials as part of an aircraft noise and land-use compatibility study, a $300,000 federally-funded operation.

Dunkelberg said the airport, which opened in a rural area of Benton County in November 1998, doesn't meet the Federal Aviation Administration's criteria as an identifiable noise problem.

The consultants said that the airport benefits from its rural location and from the use of the regional jets. Regional jets operate quieter than bigger planes, Reeves said. The airport averages 45.5 daily departures, and 22.6 are regional jets, according to the study. Larger planes, such as military jets, make up less than 10 percent of the average daily departures. "Compared to most commercial airports, it's quieter here," Reeves said. "Regional jets are wonderful from a noise perspective."