A Pilot Study on the Human Body Vibration Induced by Low Frequency Noise

Yukio TAKAHASHI*, Yoshiharu YONEKAWA1, Kazuo KANADA1 and Setsuo MAEDA2

1 National Institute of Industrial Health, 6–21–1, Nagao, Tama-ku, Kawasaki 214-8585, Japan
2 Human Factors Research Unit, Department of Industrial Engineering, Faculty of Science and Technology, Kinki University, 3–4–1, Kowakae, Higashiosaka, Osaka 577-8502, Japan

Received October 1, 1998 and accepted November 6, 1998

Abstract: To understand the basic characteristics of the human body vibration induced by low frequency noise and to use it to evaluate the effects on health, we designed a measuring method with a miniature accelerometer and carried out preliminary measurements. Vibration was measured on the chest and abdomen of 6 male subjects who were exposed to pure tones in the frequency range of 20 to 50 Hz, where the method we designed was proved to be sensitive enough to detect vibration on the body surface. The level and rate of increase with frequency of the vibration turned out to be higher on the chest than on the abdomen. This difference was considered to be due to the mechanical structure of the human body. It also turned out that the measured noise-induced vibration negatively correlated with the subject's BMI (Body Mass Index), which suggested that the health effects of low frequency noise depended not only on the mechanical structure but also on the physical constitution of the human body.

Key words: Low frequency noise, Human body vibration, Body surface, Miniature accelerometer, Chest, Abdomen, Body mass index (BMI)

Introduction

In current standards1,2) the A-weighted sound pressure level is provided as a basic quantity for measuring and evaluating noise in the working environment. This quantity is calculated based on the A-weighting curve designed in accordance with the human equal-loudness level contours3) and it is therefore useful for measuring noise and evaluating a worker's risk of noise-induced hearing loss.

On the other hand, this evaluation focusing on audible noise results in underestimating low frequency noise4–8), by which in this paper we mean noise with a frequency range below 100 Hz, including infrasound (below 20 Hz). Low frequency noises are prevalently generated, occasionally with very high levels such as 100 dB (SPL) or more, in various working environments. They originate, for example, in compressors, blowers, engines, air-conditioning systems, ventilation systems and so on. In spite of the prevalent generation, they have not attracted much attention, because the human hearing threshold levels are quite high3) and a worker’s hearing ability is hardly impaired by them.

Apart from the effects on the ear, some evaluating curves focusing on low frequency noise, such as the LFNR curve9), the LF curve10) and so on, have been proposed and the G-weighting curve11) was standardized for infrasound in 1995. They are useful for evaluating temporary psychological effects such as an uncomfortable feeling, because they are designed in accordance with psychological and perceptual responses of human beings, but these responses are expected to be gradually reduced as habituating to the noise takes place. Many workers serve at their workplaces for more than ten years and it is important for them to evaluate the noise from the standpoint of preventing its chronic and physical health effects such as hearing impairment. It is preferable
for low frequency noise in the working environment to be evaluated on the basis of some unchangeable human responses during long term exposure to it.

From this standpoint, we take note of a vibratory sensation that a man perceives when exposed to low frequency noise. It is considered to be reasonable that this vibratory sensation originates in the human body vibration induced by some external vibratory stimulus. Although its level is supposed to be lower than that of the vibration caused when operating an industrial tool or machine, this noise-induced vibration is expected to be an important and useful quantity for evaluating the possible chronic health effects of low frequency noise, because (1) it is a physical and mechanical response of the human body and expected not to be reduced during long term exposure, (2) it is considered to be induced not only on the body surface but also in the inner body such as the internal organs. To the authors' knowledge, few studies on measuring it have been made so far. It is therefore important to investigate its basic characteristics and if an evaluating method were established in accordance with it, the method, together with existing psychological ones, would also enable us to evaluate a number of other aspects of low frequency noise in the working environment.

For this purpose, noise-induced vibration should be measured in the inner body such as the internal organs, but this is technically difficult. As a first step, we designed a method to measure noise-induced vibration on the body surface and carried out preliminary measurements. The results proved to be useful in understanding the basic characteristics such as the dose-response relationship, frequency-dependency, and so on. The measuring method and the results of the preliminary measurement are reported and discussed in this paper.

Materials and Methods

Preliminary measurements were carried out in the test chamber (3.16 m x 2.85 m x 2.8 m) of the infrasound experiment system13 shown in Fig. 1. Six healthy males whose ages ranged from 24 to 57 (mean=37.0, SD=12.5) participated. Four measuring positions, two on the chest (2 cm above the right and left nipples) and others on the abdomen (5 cm under the pit of the stomach, and 5 cm to the right and left of the midline), were selected because they were in the area above the prime internal organs, such as the lungs and stomach. At each measuring position, acceleration perpendicular to the body surface was detected as a measure of the noise-induced vibration.

A miniature accelerometer (EGA-125-1OD, Entran, USA), which is designed to detect an acceleration in one direction, was utilized as a vibration detector. In detecting the surface vibration with an accelerometer, it is a condition that mounting it on the surface does not change the local vibrating system around it. Since it has been verified that this condition can be achieved by using a small, light instrument14,15, the accelerometer we adopted was very small (3.56 mm x 6.86 mm x 3.56 mm) and lightweight (0.5 g), and we attached it to the measuring position with double-sided adhesive tape and no other supporting material. Because the largest area of the accelerometer (3.56 mm x 6.86 mm) contacted the body surface, we could prevent its unstable motion. Its resonance frequency was 500 Hz according to the manufacturer's specification, which was more than adequate for our purpose. We also confirmed that the accelerometer itself hardly vibrated under exposure to low frequency noise stimuli.

The output signal of the accelerometer was fed to a strain amplifier (6M92, NEC Medical Systems, Japan), where it was low-pass filtered (cutoff frequency=100 Hz) to reduce electrical noise and amplified. The measurements at 4 positions were carried out simultaneously with 4 identical sets each of which consisted of a miniature accelerometer and a strain amplifier. Each set was calibrated in advance, mounting the accelerometer on a vertical vibration table (AST-11V, Akashi, Japan) with a calibrated acceleration pickup (PV-85, Rion, Japan) and a vibration meter (VM-80, Rion, Japan).

The output signals of the strain amplifiers were recorded
on DAT (Digital Audio Tape) with a data recorder (PC216Ax, Sony Precision Technology, Japan).

Fifteen kinds of the low frequency noise stimuli (5 frequencies × 3 sound pressure levels) were reproduced by 12 loud speakers\(^{13}\) (TL-1801, Pioneer, Japan) installed in the wall in front of the subject (Fig. 1). All of them were pure tones the frequencies of which were 20, 25, 31.5, 40 and 50 Hz, and the sound pressure levels of which were 100, 105 and 110 dB (SPL), respectively. The input to the loud speakers was adjusted so that the desired sound pressure level could be measured at the center of the test chamber, 100 cm high (corresponding to the chest of a subject sitting on a chair), without a subject present. During the measurement the sound pressure levels of the noise stimuli were monitored by a low frequency sound level meter (NA-17, Rion, Japan) in the test chamber (Fig. 1). The levels of higher harmonics of the noise stimuli had been turned sufficiently low when the stimuli were reproduced at the levels of 110 dB or less\(^{13}\).

The subject who wore no clothes on the upper half of the body to allow the accelerometers to be attached was exposed to the noise stimuli sitting on a chair at the center of the test chamber (Fig. 1). He sat erect on the chair with his back more than 10 cm from its backrest. The temperature in the chamber was initially set at 25°C at his position (not controlled to be uniform in the whole of the chamber) and, if he complained, adjusted within the 23–27°C range to keep him comfortable and prevent him from sweating. The humidity in the chamber could not be controlled because of lack of the equipment to control it but we verified that it was stable within the 25–35% range. The illuminance in the chamber was about 90 lx at the center of it, 100 cm above the floor.

The subject was instructed to be in the test chamber for 10 min before the measurement in order to adjust to the temperature and atmosphere. After the adjusting period, the accelerometers were attached and the measurement started. At first the inherent vibration with no noise stimulus was recorded (1 min). And then a rest period with no noise stimulus (1 min) and an exposure period with a noise stimulus (1 min) when the vibration at each measuring position was recorded were continued alternately. Fifteen kinds of noise stimuli were presented in random order for every subject.

The data recorded on DAT were analyzed by means of an FFT analyzer (HP3566A, Hewlett Packard, USA) and the power spectrum was obtained for every measuring position and every noise stimulus, including no exposure. For eliminating the transient responses corresponding to the beginning and end of each stimulus, only a 40-second length of each set of data was analyzed by neglecting the head (10 s) and tail (10 s) parts. In the case of a noise stimulus, a spectral component (mV) at the frequency corresponding to the stimulus was converted to an acceleration (m/s\(^2\)) (r.m.s.), being multiplied by a conversion coefficient obtained in the calibration measurement. In the case of no noise stimulus, spectral components at five frequencies (20, 25, 31.5, 40 and 50 Hz) were converted to accelerations.

This study was approved by the institutional ethical inquiry committee established in conformity to the Declaration of Helsinki\(^{16}\), and informed consent of each subject was obtained before measurement.

**Evaluation of the Methods**

Figure 2 shows typical examples of the power spectra obtained on the left chest of a subject. Figure 2 (a) corresponds to the case of no exposure and Fig. 2 (b) corresponds to the case with exposure to 50 Hz, 100 dB noise stimulus. Remarkable spectral components appearing around 10 Hz, which were found for all of the subjects independently of the noise stimuli, were considered to originate in the heart beat. Because these inherent spectral components were larger than the noise-induced ones, the measuring method was proved not to be applicable to measurement in a frequency range lower than 20 Hz.

Inherent spectral components turned out to be very small (Fig. 2 (a)) in the frequency range higher than 50 Hz for all the subjects, whereas another difficulty was noticed in this frequency range. The poor uniformity of the sound pressure levels in the test chamber\(^{13}\), which is one of its intrinsic properties, possibly made it difficult to condition the sound pressure levels bordering on the subject's body surface to be homogeneous. This was difficult to improve and resulted in limiting the upper limit of the frequency range of the noise stimuli to 50 Hz.

In the frequency range from 20 to 50 Hz, the measuring method was proved to be sensitive enough for our purpose. As shown in Fig. 2 (b), an evident peak of the noise-induced vibration was found at the frequency corresponding to the noise stimulus (50 Hz, 100 dB). But, because the phase relationship between the noise-induced vibration and the inherent one was unknown, the noise-induced spectral component was simply converted to an acceleration without subtracting the amount of the inherent one in any of the cases. Therefore, the measured accelerations were probably contributed by the inherent components and the contribution
was supposed to be larger at lower frequencies (20 and 25 Hz). For verifying the significance of the measured accelerations (means ± SD), statistical analysis (ANOVA followed by multiple comparison) with SPSS software was performed on the difference between the measured accelerations and the inherent one for every measuring position. The results of the statistical analysis are discussed below.

Results

Here only the results obtained on the left half of the body (on the left chest and on the left abdomen) are shown because no difference was found between the results obtained on the right half of the body and those on the left. The noise-induced vibrations corresponding to higher harmonics of the noise stimuli could not be detected in the frequency range up to 100 Hz in any of the cases.

Tables 1 and 2 show the results of the statistical analysis mentioned previously. For 110 dB, all the accelerations measured with the noise exposure were significantly (p<0.01, two-sided) larger than the inherent ones with no exposure. At higher frequencies (31.5, 40 and 50 Hz), almost all of the accelerations measured on the chest with the noise exposure, except in the case of 40 Hz, 100 dB stimulus, were significantly (p<0.05, two-sided) greater than the inherent ones (Table 1). On the abdomen (Table 2), similar results were obtained at still higher frequencies (40 and 50 Hz). These results showed clearly that the unusual vibrations were induced on the human body by low frequency noise, but distinguishing them from the inherent ones was difficult in lower frequencies and at lower sound pressure levels.

In Figs. 3 and 4, the measured accelerations (means ± SD) are presented in terms of an acceleration level defined as

\[
\text{Acceleration level} = 20 \log_{10} \left( \frac{a}{a_p} \right)
\]
where $a$ is a measured acceleration ($\text{m/s}^2$ (r.m.s.)) and $a_0$ is the reference acceleration equal to $10^{-5} \text{ m/s}^2$. This unit was used here because it was expected to correspond closely to the noise stimuli reproduced by a 5 dB step. The measured acceleration levels were found to increase with frequency and the sound pressure level both on the chest (Fig. 3 (a)) and on the abdomen (Fig. 3 (b)). The rates of increase with frequency were calculated for every position and the sound pressure level in the frequency range from 31.5 to 50 Hz, to eliminate the effect of the inherent vibration, and averaged over three sound pressure levels to be 13 dB/oct. on the chest and 8.5 dB/oct. on the abdomen, respectively. The increase step in the measured acceleration levels was found to be about 5 dB, which was in good agreement with the increase step (5 dB) in the sound pressure levels. At frequencies above 31.5 Hz, the amplitudes of the acceleration levels measured on the chest were apparently about 10 dB larger than those on the abdomen, but at lower frequencies

![Graphs](image-url)

**Table 1.** Statistical significance of the difference between the noise-induced accelerations (means ± SD) measured on the left chest and the inherent ones with no exposure

<table>
<thead>
<tr>
<th>Sound pressure levels (dB)</th>
<th>Measured accelerations (m/s² (r.m.s.))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>At 20 Hz</td>
</tr>
<tr>
<td>No exposure</td>
<td>0.011 ± 0.005</td>
</tr>
<tr>
<td>100</td>
<td>0.014 ± 0.007</td>
</tr>
<tr>
<td>105</td>
<td>0.015 ± 0.006</td>
</tr>
<tr>
<td>110</td>
<td>0.023 ± 0.010**</td>
</tr>
</tbody>
</table>

ANOVA followed by multiple comparison was performed with SPSS software. *p < 0.05, **p < 0.01 (two-sided).

**Table 2.** Statistical significance of the difference between the noise-induced accelerations (means ± SD) measured on the left abdomen and the inherent ones with no exposure

<table>
<thead>
<tr>
<th>Sound pressure levels (dB)</th>
<th>Measured accelerations (m/s² (r.m.s.))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>At 20 Hz</td>
</tr>
<tr>
<td>No exposure</td>
<td>0.017 ± 0.007</td>
</tr>
<tr>
<td>100</td>
<td>0.020 ± 0.009</td>
</tr>
<tr>
<td>105</td>
<td>0.021 ± 0.010</td>
</tr>
<tr>
<td>110</td>
<td>0.034 ± 0.012**</td>
</tr>
</tbody>
</table>

ANOVA followed by multiple comparison was performed with SPSS software. *p<0.05, **p<0.01 (two-sided).

![Graphs](image-url)

Fig. 3. The measured acceleration levels (means ± SD) plotted as a function of frequency.
(a) on the left chest and (b) on the left abdomen. They were found to increase with frequency and the sound pressure level. No difference was found between the results on the right half and those on the left half of the body.

Industrial Health 1999, 37, 28–35
HUMAN BODY VIBRATION INDUCED BY LOW FREQUENCY NOISE

(20 and 25 Hz) the difference between them was not clear because of large inherent vibrations.

Since the noise-induced vibration is a mechanical response to the noise, its characteristics are supposed to depend on the mechanical characteristics of the human body. To verify this, the acceleration levels measured with the noise stimuli at the levels of 100 and 110 dB are plotted as a function of the subject's BMI in Fig. 4. The BMI (Body Mass Index), which is defined as

\[ \text{BMI} = \frac{W}{H^2} \]

where W is the weight (kg) and H is the height (m), is a quantity in close correlation with the amount of fat in the body and prevalently utilized as an index of obesity. The fat is considered to contribute to the mechanical characteristics, such as stiffness, of the human body. As shown in Figs. 4 (a) and (b), the acceleration level measured on the chest negatively correlated with BMI at higher frequencies (40 and 50 Hz) but no apparent correlation was found at lower frequencies (20, 25 and 31.5 Hz). On the abdomen, a negative correlation with BMI was found at all frequencies.

Discussion

The maximum measured accelerations were 0.17 m/s² (r.m.s.) on the chest and 0.062 m/s² (r.m.s.) on the abdomen, respectively, both of which were measured with 50 Hz, 110 dB noise stimulus (Tables 1 and 2). By multiplying them by the weighting factor, equal to 0.0388 at 50 Hz, for the whole-body horizontal vibration standardized as ISO 2631-

Fig. 4. The measured acceleration levels plotted as a function of the subject's BMI.
(a) on the left chest, for 110 dB noise stimulus, (b) on the left chest, for 100 dB, (c) on the left abdomen, for 110 dB and (d) on the left abdomen, for 100 dB. On the chest, the acceleration levels negatively correlated with BMI at higher frequencies (40 and 50 Hz), whereas no apparent tendency was found at lower frequencies (20, 25 and 31.5 Hz). On the abdomen, a negative correlation with BMI was found at all frequencies.
1\(^{(17)}\), they are converted to the weighted r.m.s. accelerations, 0.0066 m/s\(^2\) (r.m.s.) and 0.0024 m/s\(^2\) (r.m.s.), respectively. These levels are lower than the level of vibration at which the health effects are expected\(^{(17)}\). Nevertheless, the noise-induced vibration is deduced to be an isotropic one because the wavelength of low frequency noise (6.8 m for 50 Hz pure tone, supposing the sound velocity to be 340 m/s) is larger than the size of a man, whereas the standard treated the vibration induced in one direction. Because of this difference, the validity of applying the standard in the case of noise-induced vibration is uncertain, and it should not be concluded that the low-level noise-induced vibration causes no health effect.

Yamada et al.\(^{(18)}\) reported that a deaf person perceived low frequency noise through a vibratory sensation on the chest. Our results shown in Fig. 3 are not in conflict with their work, but rather confirm it quantitatively, though evident consistency is not proved because of the small number of measuring positions in our study. Higher acceleration levels and steeper rates of increase with frequency measured on the chest are presumed to result from easier induction of a vibration on the lung which is organized like a balloon and linked to the atmosphere through the airway. Figure 3 (a) implies that the acceleration levels measured on the chest still increase in frequency ranges higher than 50 Hz. Wodicka et al. showed experimentally\(^{(19)}\) and theoretically\(^{(20)}\) that the acceleration measured on the posterior chest wall peaked in the frequency range between 100 and 200 Hz when a noise stimulus with a frequency range above 100 Hz was injected directly into the subject’s mouth. Apart from different experimental conditions, their results suggest that the noise-induced vibration on the chest increases further, up to frequencies around 150 or 200 Hz.

On the abdomen, on the other hand, the noise-induced acceleration levels were lower (by about 10 dB) than those on the chest at frequencies above 31.5 Hz (Fig. 3) and their rates of increase with frequency were gentler. It is deduced that crowding of the internal organs and tissue in the abdomen hinders induction of a vibration. In connection with abdominal vibration, Abrams et al. carried out a series of interesting experiments from a viewpoint concerned about the effect on a fetus. They applied the vibration stimulus\(^{(21–23)}\) and the noise stimulus\(^{(24)}\) to the abdomen of a ewe, as a model for a woman, and measured the vibration (sound pressure) within the abdomen. As a result, they proved that the vibration (sound pressure) with a frequency range below 100 Hz hardly attenuated and penetrated into the deeper regions of the abdomen. Similar less attenuation of vibration was also found for the human uterus\(^{(25)}\). Apart from the gender difference, their results imply that the abdominal noise-induced vibration in our measurement is promoted in frequency ranges below 100 Hz.

In discussing noise-induced vibration, it is important to consider its generating and propagating mechanism in the human body. The mechanism was not clarified by our results, but Fig. 4 implies that the fat in the body damps the vibration or obstructs its propagation through the body. Figure 4 also suggests that these damping characteristics are position-dependent and frequency-dependent. Although we cannot affirm that BMI is the most appropriate index of the relationship between noise-induced vibration and the physical constitution of the human body, these results suggest that the characteristics of noise-induced vibration depend not only on the mechanical structure but also on the physical constitution of the human body.

In this study we measured noise-induced vibration on the chest and the abdomen with a measuring method we designed. The result suggested that its basic characteristics depended on the mechanical structure and physical constitution of the human body. In other words, it appeared that the mechanical characteristics of the human body were important factors in evaluating low frequency noise from the standpoint of its health effects. Nevertheless, it remains unknown how vibrations measured on the body surface are related to vibrations in the body such as the internal organs, for which it cannot be concluded what chronic health effects are caused by long term exposure to low frequency noise. In addition, the characteristics of noise-induced vibration are supposed to depend on other factors such as the subject’s posture, gender difference, temperature, humidity and so on. Further detail investigations are desired in order to understand all of the characteristics of noise-induced vibration and to relate them to vibration in the inner body and the health effects on man.

**Acknowledgments**

This study was supported in part by a fund from the Environmental Agency of Japan.

**References**


*Industrial Health 1999, 37, 28–35*


