Improvement of Occupational Noise-induced Temporary Threshold Shift by Active Noise Control Earmuff and Bone Conduction Microphone

Seichi HORIE

Department of Health Policy and Management, Institute of Industrial Ecological Science, University of Occupational and Environmental Health, Japan

Abstract: Improvement of Occupational Noise-induced Temporary Threshold Shift by Active Noise Control Earmuff and Bone Conduction Microphone: Seichi HORIE. Department of Health Policy and Management, Institute of Industrial Ecological Science, University of Occupational and Environmental Health—A newly devised earmuff that utilizes an active noise control system and a bone-conduction microphone was examined in an actual working environment where workers are required to communicate under noisy conditions. Thirteen experienced male workers aged 26 to 46 (mean $\pm$ SD; 37.5 ± 5.8) engaged in manufacturing steel pipes participated in the study. For 4 h working in a noisy environment (92 to 103 dBA), they used the conventional device (an earphone on one ear and an earplug in the other, and an ordinary microphone) or the new device. After wearing the new device, the temporary threshold shift (TTS) at 4 kHz was lowered ($p < 0.045$, Wilcoxon's sign rank test) and the number of workers who had TTS was reduced in all frequencies examined ($p < 0.001$, two-way repeated-measures ANOVA). Many workers evaluated the new device superior to the conventional one especially in its "clearness of voice," but they did not give the new device a good overall rating mainly because of its heaviness. Although the new device needs improvement, it appears promising as a hearing protector.

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Key words: Temporary threshold shift, Hearing protection, Earmuff, Active noise control, Bone conduction, Speech intelligibility

Among the hazardous factors in the workplace, noise is one of the most difficult to eliminate because enclosure or reduction of its source is often infeasible. This may underlie the fact that many workers are exposed to noise and develop hearing problems. For instance, in Japan, in the year 2000 alone, at least 208,000 workers were exposed to noise and more than 36,000 (17%) of them were found to have abnormalities on audiometric examination¹⁾. Furthermore, once a worker develops hearing loss, there is no effective medical treatment. Therefore the primary prevention is of the utmost importance. To achieve this, the most practical method seems to be the proper use of hearing protectors such as earplugs or earmuffs. Nevertheless, in actual workplaces, workers would not always use protectors because they feel that it causes difficulty in detecting irregularities in machine operation or in communicating with colleagues^{2, 3)}.

There seem to have been two important techniques that are applicable to hearing protectors of a reasonable price. One is a real time active noise control system that suppresses noise by generating out-of-phase signals^{4–6)}. Another is a bone-conduction microphone that detects vibration of the skull caused by the speaker's voice. Due to rapid advances in digital signal processing, both techniques have become widely available at modest cost. Meanwhile, a number of studies have indicated the importance of field measurement for evaluating the effectiveness of hearing protectors^{7, 8)}. Therefore, this study was performed to devise a new earmuff combining these new techniques and to evaluate its effectiveness by comparing it with a conventional hearing protector subjectively and objectively in an actual working environment.

Methods

Subjects and working environment

I focused on one of the noisiest workplaces in a steel manufacturing company where 14 males were engaged.

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Correspondence to: S. Horie, Department of Health Policy and Management, Institute of Industrial Ecological Science, University of Occupational and Environmental Health, 1-1 Iseigaoka, Yahatanishi-ku, Kitakyushu 807-8555, Japan

I fully explained the experiments to all workers there and all of them agreed to participate, but one subject was excluded because he had a hearing threshold greater than 30 dB at 1 kHz and 40 dB at 4 kHz on a regular health examination. The remaining 13 subjects had lower hearing thresholds in both frequencies and less than a 20 dB difference in bilateral ears. They had no tinnitus, otitis media or other disturbances that might affect hearing acuity. The age ranged 26 to 46 (mean $\pm$ SD; 37.5 ± 5.8). They had worked in the same factory for 5 to 26 years (mean $\pm$ SD; 16.8 ± 5.4) and had received a regular health examination every year since they were hired.

They all work in 2 shifts for approximately 8.5 h per day with a 45-min lunch break, 5 d per wk. Their tasks (checking the size, shape and surface of the pipes to remove improper products) are carried out in a limited area within 2 m of the production line, so that they spend most of their working hours in a very noisy environment. Machine air blow and collision of pipes while being rolled and bundled are the main source of noise. The workers have to wear a half-face mask and a pair of goggles for protection from ferroxiide dust, and yet have to communicate from time to time with their co-workers who work 2 to 20 m away.

Measurement of noise, audiometry and subjective evaluation

A Rion NA-29E sound-level meter was used to measure the noise in the environment, and a Rion AA61-BN pure-tone audiometer for audiometry. Both meters were calibrated at regular intervals by the manufacturer.

The audiometer was placed in an office building close to the workplace. The background noise level of the room was 33.9 to 39.1 dBA (mean $\pm$ SD; 36.4 ± 2.1) with a central octave band frequency of 125–250 Hz, which was the quietest environment in the building available for the audiometry. The hearing threshold was measured in the ear on the side where the examined worker usually inserted the earphone of the conventional hearing protector. From 7:15 to 7:30 in the morning, the pre-work audiometry was performed. At noon on the same day immediately after work, the subject was asked to hurry to the office so that the post-work measurement could be completed within 2 to 7 min after exposure to the noise ceased in the workplace.

I had a structured interview with each subject after the worker had used 2 devices to obtain subjective evaluation by the worker.

Protector

Two types of hearing protectors with a communication device were used. One consisted of an earphone and an oral microphone for radio communication among co-workers (IWP-5600, Iwatsu Electric), which the workers were ordinarily using there (Fig. 1a). The voice is picked

up by the oral microphone placed in front of the worker's mouth and electrically transmitted to the earphones of others. The ear on the other side was protected by an ear plug (No.15, Koken; EP12, Shigematsu Works; 1100, Sumitomo 3M).

The newly devised protector was made of an earmuff that had an active noise control system (Proactive PA-3100, Shigematsu Works) with a small speaker and of a helmet inside the top of which a bone conduction microphone (CC-11, Shigematsu Works) was placed (Fig. 1b). The bone-conducted vibration generated by the voice of the worker is picked up by the bone conduction microphone and electrically transmitted. The earmuff had an active noise control system inside a large circumaural earcup, which attenuates noises in the frequency range below 500 Hz. The noise sampled inside the earmuff is processed to produce an anti-noise signal of the same amplitude but 180 degrees out of phase. The small speaker inside the earmuff generates the anti-noise signal along with the speech signal. According to the manufacturer, combined with passive noise reduction capacity, the earmuff attenuates audible frequencies over 100 Hz by 25–43 dB. The new device weighed a total of 850 g. Since the earmuff and helmet cannot be separated, the worker wears the earmuff as long as he uses the helmet. The speaker and the microphone were connected by small cables to an amplifier and a rechargeable battery in the earmuff.

Data analysis

The temporary threshold shift (TTS), which is regarded as the predictor of future development of noise-induced hearing loss, was calculated: $TTS = \text{post-work hearing threshold} - \text{pre-work hearing threshold}$ at the same frequency. Wilcoxon sign rank test and two-way repeated-measures ANOVA were carried out to compare the TTS values under two sets of conditions with a conventional device and the new device. The result of the closest health examination, relevant to microcirculation, was obtained with permission from the subjects to analyze the relationship between these indices and TTS at 4 kHz. Linear regression analysis was performed for the analysis. Statistical analysis was carried out on StatView version 5 or SAS Release 6.12 (SAS Institute, Cary, NC). For drawing graphs, Prism version 2.01 (GraphPad Software, San Diego, CA) and Origin 6.0J (Microcal Software, Northampton, MA) were used.

Results

Noise in the environment

The octave band sound pressure levels of the workplace are shown in Fig. 2. A-weighted sound pressure ranged 92 to 103 dBA. As these field measurements of noise were performed at the subjects' actual position, the observed levels were estimated to be almost equivalent

Fig. 1. The left upper figure (a) is an ordinary communication device with an earphone and an oral microphone. The right lower figure (b) is the newly devised protector with an active noise control earmuff and a bone conduction microphone attached at the top inside the helmet.

to those to which each subject was exposed. Even inside the operation room they often exceeded 80 dBA. The noise recorded at the entrance, 30 m from the working area, was 75 to 80 dBA.

Audiometry

Before work, except for one worker who had a threshold of 45 dB at 8 kHz, all had a threshold lower than 40 dB at all frequencies (Fig. 3). When a "dip" was defined as a hearing threshold increased by more than 10 dB compared with that at the higher frequency, 3 workers had a dip at 6 kHz, one at 4 kHz, and another at 2 kHz. The pre-work hearing threshold in each worker did not differ by more than 10 dB at any frequency in two measurements on different days (one when the conventional device was used and another when the new device was examined), and neither the mean ($\pm$ SD) nor the median values for the pre-work threshold were significantly different.

After work, when wearing the conventional device, the hearing thresholds (dB, mean $\pm$ SD) at 1, 2, 4, 6 and

Fig. 2. Noise inside the operation room (Δ), at entrance of the factory ($\square$), and at the worker's position ($\bullet$). The noise at the worker's position was measured repeatedly (once every 2 wk for 3 months while the present study was carried out), and the mean frequency is shown as a bar.

* all: A-weighted sound pressure level under all pass condition (dBA)

8 kHz were 18.8 ± 7.4 , 21.9 ± 6.6 , 26.5 ± 9.7 , 26.2 ± 12.4 , and 25.8 ± 10.0 , respectively ($n=13$ at all frequencies). A dip was seen in two workers at 6 kHz and in other two at 4 kHz. When the workers wore the new device, the hearing thresholds (dB, mean $\pm$ SD) after work at 1, 2, 4, 6 and 8 kHz were 16.2 ± 8.7 , 17.3 ± 9.5 , 19.6 ± 10.7 , 21.9 ± 13.5 , and 23.8 ± 10.6 , respectively ($n=13$ at all frequencies). Three workers had a dip at 6 kHz and another two at 4 kHz.

Temporary threshold shift (TTS)

After using the conventional device, 12 workers had a TTS of 10 dB or more, most frequently at 4 kHz (Fig. 4). The largest TTS observed was 25 dB at 4 kHz. With the new device, 7 workers had a TTS of 10 dB or more, most frequently at 4 kHz. The largest TTS recorded was 20 dB at 4 kHz. The median TTS at 4 kHz was significantly lower ($p<0.045$, by the Wilcoxon sign rank test) when the workers wore the new device.

Four workers reported that they could not wear the new device for 4 h continuously due to its heaviness, tightness or humidity within the helmet and that they took off the device for about 10 min, staying inside the operation room, but none of them had tinnitus, or other symptoms suggesting sudden loss of hearing. The TTS in these workers did not differ from those in other subjects at any frequency.

The number of subjects with a TTS was smaller at all frequencies examined on wearing the new device (Fig. 5). Comparing them as two groups, the difference was found statistically significant ($p<0.001$, by the two-way

Fig. 3. Hearing threshold determined with a pure tone audiometer at 1, 2, 4, 6 and 8 kHz before and after 4-h work in a noisy workplace wearing a conventional device (●) and the new device (earmuff with bone conduction microphone)(○). It should be noted that some symbols and lines are completely overlapped (n=13 in each group).

repeated-measures ANOVA).

Subjective evaluation

Almost 70% or more workers considered the new device better in attenuating noise from the environment, in smaller background noise, and in clearness of human voice (Table 1). Nevertheless, no one preferred the new device concerning fitting to the head. As for mobility during work and general comfortableness, more workers

liked the conventional device. In the overall rating, a few workers felt no difference between the new and conventional device. But most workers evaluated the new device inferior to the conventional one. The main reason was its heaviness. Some pointed out that lateral protrusion disturbed the work and that the bone conduction microphone caused pain.

Fig. 4. Temporary threshold shift (TTS) at each frequency determined audiometrically after using the conventional or the new device (earmuff with bone conduction microphone). The bar indicates the median in each group. * $p < 0.045$, # $p < 0.055$ compared with TTS after wearing the conventional device (Wilcoxon sign rank test).

Relationship to results of general health examination

None had blood pressure exceeding 140 mmHg systolic and 90 diastolic. Ten of them were smokers, one pack a day or more. Other results (mean $\pm$ SD, $n=13$) obtained were; BMI (22.5 ± 2.7 kg/m²), GOT (25.2 ± 16.5 U/l), GPT (32.3 ± 23.4 U/l), γ -GTP (54.8 ± 77.9 U/l), total cholesterol (170.8 ± 22.8 mg/dl), high density lipoprotein cholesterol (58.8 ± 13.1 mg/dl), and hemoglobin (14.7 ± 1.5 g/dl). There were no linear correlations between BMI or any of the blood indices above expressed in logarithmic scale and the TTS at 4 kHz observed with either the

Fig. 5. Number of workers who had TTS at each frequency determined audiometrically after using the conventional (filled column) and the new device (earmuff with bone conduction microphone)(open column). On comparing the effects of the two devices, the difference was significant ($p < 0.001$, in two-way repeated-measures ANOVA).

conventional or new device.

Discussion

Since the main purpose of the present study is to evaluate a hearing protector subjectively as well as objectively, and since I wished to avoid unnecessary exposure, I asked for the cooperation of experienced workers in a very noisy workplace who had no apparent hearing problems. In addition, because those workers had had audiometric examinations in the past regular health examinations with an instrument of the same type (pure-tone audiometer) as in the present study, improper response to audiometry or differences in learning effects among the subjects could be minimized. But because of these, the number of subjects was limited and might have led to a selection bias, i.e., workers more tolerant of noise⁹⁾ might have been selected.

Although the exact relationship between TTS and noise-induced permanent threshold shift has not been

Table 1. Subjective evaluation by workers

	Conventional device better	No difference	New device better
Noise attenuation	0	4	9
Suppression of background noise	0	2	11
Clearness of voice	2	2	9
Fitness	4	9	0
Mobility at work	6	4	3
Comfort	10	2	1
Overall choice	10	3	0

Numbers indicate those of workers (total of 13) who chose the answer in the interview.

clarified, TTS is generally believed to be an indicator of probable development of hearing loss¹⁰⁻¹³. The TTS value 2 min after 8 h of noise exposure is assumed to be equivalent to the level of hearing loss after ten years¹², and other previous studies showed that noise in a working environment could cause TTS in workers there¹⁴⁻¹⁷. On the other hand, the magnitude and the pattern of the development of TTS can be affected by various factors¹⁸ including the structure of the outer ear¹⁹, body temperature²⁰, physical exercise²¹, cigarette smoking^{22, 23}, diseases related to microcirculation^{24, 25}, race^{26, 27}, and the existence of a high permanent threshold shift, which is generally believed to lower TTS²⁸. Although the effects of those factors could not entirely be ruled out, smoking habit, blood pressure and indices relevant to the microcirculation did not appear to have a significant effect on the TTS values in the subjects of the present study. Some workers in this study already had high hearing thresholds at 6 kHz and 8 kHz before work and they had a rather different pattern of TTS than others, but I did not exclude those data from the analysis in order to have the results cover most workers in the same workplace and to avoid selection bias.

In spite of the limitations mentioned above, when workers used the new device, it decreased the degree of TTS at 4 kHz compared to that observed with the conventional device. In addition, the number of workers with TTS was smaller at all frequencies examined with audiometry. The new device therefore appears to be effective as a protector. Nevertheless, TTS could be only partly suppressed even with the new device. Since broadband noise causing TTS is generally considered to be greater than 78 dBA²⁹, the broadband noise might have reached this level within the earmuff due to its very high pressure of the environment. According to the equation for predicting the average growth of TTS given by Takagi *et al*³⁰ and its recovery¹³, the average TTS at 5 min after noise exposure in the workplace in this study should have been 34.6 dB at 4 kHz, applying the estimated spectrum level of noise exposure at 3,040 Hz calculated with the empirical exponential formula derived from the noise exposure data for 1 kHz to 8 kHz in this study. The observed average TTS at 4 kHz was 23.1 dB lower with the conventional device, and 27.0 dB lower with the new device. These values correspond to a noise attenuation level of 9.7 dB at an octave band level centered at 3,040 Hz with the conventional device, and likewise 12.3 dB with the new device. The observed discrepancy between the attenuation capacity of the hearing protector measured under actual work conditions and measured under laboratory conditions were also reported in a previous study³¹. Improper wearing of the device cannot be ruled out because several workers pointed out that the device did not fit the head very well. Moreover, most of the noise frequency was higher than 500 Hz. Because there

were rapidly fluctuating noises, it was likely that the active noise cancellation mechanism installed in the device was not fully effective in suppressing TTS.

It is understandable that many workers preferred the conventional hearing protector to the new device concerning as to comfort or mobility at work, since it consisted of an ordinary earphone and microphone, both of which are light and easy to wear. Apparently, there seems to be a large discrepancy between the results for TTS and subjective evaluation of communicability by the workers; whereas TTS was moderately lowered by the new device only at 4 kHz, the workers supported it overwhelmingly concerning noise attenuation, suppression of background noise and clearness of voice. It is likely that the active noise cancellation system and the bone-conduction microphone could effectively suppress noise in the vocal frequency band to improve "clearness of voice". To clarify these, many more experiments on a greater number of subjects are necessary, including a speech recognition test^{32, 33}, the loudness-balance method³⁴, or direct measurement of noise inside the ear canal³⁵.

Obviously the new device needs several improvements before its extensive use in the workplace is considered, because the heaviness, pain and instability claimed concerning it could be even disadvantageous to safety and productivity. It must be made lighter and fit each worker's head better so that the worker can wear it more easily with better insulation of environmental noise. The battery should be removed from the earmuff. The bone conduction microphone might be placed on one side of the helmet so that it may not cause pain. These improvements seem not to be very difficult and they will make the device not only more comfortable and wearable for workers but will most certainly suppress TTS better.

One of the advantages of the new device utilizing a bone conduction microphone is clearness of the transmitted human voice. This can reduce miscommunication in the workplace and the worker can concentrate on his or her work better. In addition, with this device, the worker can wear other personal protectors such as a half-face mask. Indeed, in an actual working environment, it is not rare that workers have to wear multiple personal protectors simultaneously and yet communicate with others. Therefore it appears that after appropriate improvements, the new device appears useful.

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