The association between low levels of lead in blood and occupational noise-induced hearing loss in steel workers

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ABSTRACT

As the use of leaded gasoline has ceased in the last decade, background lead exposure has generally been reduced. The aim of this study was to examine the effect of low-level lead exposure on human hearing loss. This study was conducted in a steel plant and 412 workers were recruited from all over the plant. Personal information such as demographics and work history was obtained through a questionnaire. All subjects took part in an audiometric examination of hearing thresholds, for both ears, with air-conducted pure tones at frequencies of 500, 1000, 2000, 3000, 4000, 6000 and 8000 Hz. Subjects' blood samples were collected and analyzed for levels of manganese, copper, zinc, arsenic, cadmium and lead with inductive couple plasma-mass spectrometry. Meanwhile, noise levels in different working zones were determined using a sound level meter with A-weighting network. Only subjects with hearing loss difference of no more than 15 dB between both ears and had no congenital abnormalities were included in further data analysis. Lead was the only metal in blood found significantly correlated with hearing loss for most tested sound frequencies ($p < 0.05$ to $p < 0.0001$). After adjustment for age and noise level, the logistic regression model analysis indicated that elevated blood lead over 7 $\mu\text{g}/\text{dL}$ was significantly associated with hearing loss at the sound frequencies of 3000 through 8000 Hz with odds ratios ranging from 3.06 to 6.26 ($p < 0.05$ – $p < 0.005$). We concluded that elevated blood lead at level below 10 $\mu\text{g}/\text{dL}$ might enhance the noise-induced hearing loss. Future research needs to further explore the detailed mechanism.

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1. Introduction

Noise-induced hearing loss is one of the most prevalent occupational conditions, as noise is one of the most pervasive occupational hazards in a wide range of industries (ACOM, 1989; ACOEM, 2003). Among workers with hearing loss, almost 30% reported that their hearing loss was related to noise at work (Stanbury et al., 2008). Furthermore, noise may act together with exposure to ototoxic agents, such as solvents, heavy metals, and tobacco smoke, to cause hearing loss (Morata, 1998; Chang et al., 2003), though the role of such cofactors remains poorly understood (ACOEM, 2003). Laboratory animal and occupational studies have demonstrated that organic solvents such as toluene contribute to occupational hearing loss and exacerbate damage from noise exposure (Lataye and Campo, 1997;

Morata et al., 1997a,b). A study found that occupational exposure to jet fuel over three years was associated with a 70% increase in the adjusted odds of hearing loss among military workers (OR = 1.7, 95% CI: 1.14–2.53). The odds ratio increased to 2.41 (95% CI: 1.04–5.57) among those with 12 years of noise and fuel exposure (Kaufman et al., 2005).

Chronic lead exposure may cause lead intoxication and result in pervasive physiological abnormalities and/or neurosensory, neuro-motor, and neurocognitive impairment in humans (ATSDR, 2007). For lead-related neuropathy, segmental demyelination and axonal degeneration are thought to be the most significant degenerating effects. These effects are manifested by distinct wrist and ankle drops and by extensor muscle palsy (Isselbacher et al., 1994). Among various lead-induced adverse health effects, one of the neurophysiological effects reported is auditory impairment, either sensory-neural hearing loss or abnormal neural transmission in the tracts and nuclei of the auditory brainstem of animals and humans (Otto and Fox, 1993; Farahat et al., 1997). A previous study that reported that bilateral brainstem auditory evoked response tests on participants with elevated blood

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lead levels (47 µg/dL) showed delayed wave latencies consistent with sensory-neural hearing impairment (Counter and Buchanan, 2002). This study also indicated that environmental noise exposure must be an important factor in determining sensory-neural hearing status in adults exposed to lead through their occupations. Additionally, another study reported that the distal auditory nerve was affected by chronic lead exposure, at a blood lead level of 30–40 µg/dL, which impaired conduction in the auditory nerve and the auditory pathway in the lower brainstem (Bleecker et al., 2003).

Previous research also reported the effect of lead and noise exposure on hearing ability with high average blood lead level of 56.9 µg/dL combined with high average noise level of 86.0 dB (Wu et al., 2000). This study implied that high, long-term lead exposure index, rather than short-term exposure, led to reductions in hearing ability. Another study also suggested that a medium blood level of 1 to 18 µg/dL was associated with hearing loss at 4000 Hz (Forst et al., 1997).

In recent years, low-level heavy metal exposure has become increasingly important, as environmental lead exposure has generally lowered in the past decades. For instance, the cord blood lead level, the monitoring index for general environmental lead exposure, decreased from 7.48 ± 2.25 µg/dL to 2.35 ± 1.12 µg/dL between 1985 and 2002 in Taiwan (Hwang et al., 2004). This occurred during the period when the country was phasing out leaded gasoline. The decrease in background blood level for a general population, as a result of reduced environmental lead exposure, offers a great opportunity to examine the association between low-level occupational lead exposure and human health. Additionally, although it is well established that lead is a neurotoxic substance, the levels and parameters of exposure required to induce neuro-ototoxicity remain to be determined. Thus, the aim of the present study was to examine the association of low level lead exposure on the hearing loss among steel workers.

2. Materials and methods

2.1. Study subjects

This study was conducted in a Taiwanese steel plant during the employees' annual health examination. In total, 412 workers were recruited. Of those recruited, 395 worked in the manufacturing zones, including the electric arc furnace, converter, vacuum oxygen decarburization, slab continuous caster, raw material feeding, and rolling. A non-exposed group of 17 workers was randomly recruited from the administration office, including the only one female worker recruited in this study. Respondents were asked to fill out a questionnaire enquiring about the data of education, cigarette smoking, alcohol drinking, and a detailed work history, including information about working conditions such as use of personal protective equipment and work-shift.

2.2. Determinations of blood metal levels

Blood samples were collected from all study subjects and stored at 4 °C until analysis in a laboratory. Blood metal levels were determined by inductive couple plasma - mass spectrometry (ICP-MS, Agilent 7500c, Agilent, Kitahachioji, Japan). The metals analyzed included manganese, copper, zinc, arsenic, cadmium and lead.

2.3. Audiometric examinations

All study subjects took part in an audiometric examination as part of the health examination. Each subject must have rested for at least 16 h without heavy noise exposure prior to participating in the audiometric examination. Standardized audiometric examination procedures were followed to determine the level of hearing loss among the study subjects with an audiometer in a testing booth where background noise level was below 30 dB (Davis, 2003). Subjects' hearing thresholds, of both

ears, were determined with air-conducted pure tones at frequencies of 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz.

2.4. Environmental measurements of airborne metal levels

Area sampling for total dust samples (NIOSH 7703) was conducted in six working zones during regular work hours, which included: electric arc furnace, converter, vacuum oxygen decarburization, slab continuous caster, mineral stock, and rolling. Dust samples were collected using 37 mm three-piece cassettes with mixed cellulose ester filter as the collecting medium. Collected dust samples were also analyzed with ICP-MS (7500C, Agilent Technologies, Inc., Japan) for the six metals previously mentioned for blood sample determination.

2.5. Noise levels at working environment

Noise levels in all working areas were measured using a sound level meter (QUEST 2900, USA) with A-weighting network. This sound level meter was calibrated by frequency prior to each measurement.

2.6. Statistical analysis

The agents that may produce hearing loss in the present study, such as noise and metal or solvents, were likely related to symmetric hearing loss rather than asymmetric loss. Thus, before further analysis, it is important to rule out asymmetric hearing loss. To determine the role of lead exposure level on hearing loss, we screened subjects such that they met the following criteria: no occupational organic solvent exposure, no congenital ear abnormality or ear-related medical history, no parental ear-related disease, and hearing loss between both ears of no more than 15 dB. Descriptive statistical data analyses were performed to understand the frequency distributions of the study subjects' levels of blood metals and hearing loss, as well as environmental levels of airborne metals and noise. Meanwhile, study subjects were grouped into three categories by blood lead level (≤ 4 , 4–7, and ≥ 7 µg/dL) and noise exposure level (<80 dB, 80 to 85 dB, and >85 dB). Then, the histogram of hearing loss level was presented by these exposure categories of blood lead level and noise exposure level. Student's *t*-test was conducted to jointly compare the association of blood lead level and the magnitude of hearing loss and the association of noise exposure and the magnitude of hearing loss. Also, correlation analyses were conducted among the following variables: blood metal levels, hearing loss levels, and environmental noise exposure levels. Logistic regression model analysis was performed to show the effects of blood lead and noise exposure levels on the odds for hearing loss by sound frequency after adjustment for age effect, with a threshold of 25 dB as criteria for hearing loss (OSHA, 2002). Meanwhile, gender, cigarette smoking, use of ear protection were also taken into consideration in the model construction to control for potential confounding.

3. Results

Table 1 summarizes the demographic information of the 412 subjects, with 259 of them fulfilling the aforementioned inclusion criteria, including 248 subjects from the manufacturing zones and 11 from the non-exposed group or administration office, and 153 subjects excluded. The 412 subjects were averaged 36.0 ± 6.5 years old. On average, they had worked for 8.6 ± 2.9 years at this steel plant. Their average body mass index (BMI) was 25.0 ± 3.5 . Among them, prevalence rates of cigarette smoking and alcohol drinking were 24.0% and 9.7%, respectively. About one-third of the subjects reported that they wore ear plugs or other kinds of hearing protection devices during their work. No significant differences in these variables were observed among individuals who met the criteria and individuals who did not meet the criteria.

Table 1
Demographic, blood metal levels, and hearing loss levels by sound frequency for the study subjects.

Variable	All subjects (n = 412)	Subjects included ^a (n = 259)	Subjects not included ^a (n = 153)
Age, year	36.0 ± 6.5	35.8 ± 6.5	36.5 ± 6.6
Seniority, year	8.6 ± 2.9	8.5 ± 3.0	8.7 ± 2.8
Height, cm	170.8 ± 5.6	170.9 ± 5.7	170.6 ± 5.4
Weight, kg	73.0 ± 11.7	72.7 ± 12.4	73.5 ± 10.2
BMI	25.0 ± 3.5	24.9 ± 3.8	25.2 ± 3.1
Alcohol drinking, %	9.7	8.5	11.8
Cigarette smoking, %	24.0	23.6	24.8
Ear protection, %	33.5	33.6	33.3
Blood metal levels, µg/L			
Mn _B	14.7 ± 5.5	14.7 ± 5.5	14.8 ± 5.6
Cu _B	725 ± 105	732 ± 112	711 ± 93
Zn _B	11097 ± 2090	11071 ± 2254	11140 ± 1784
As _B	6.85 ± 3.25	6.85 ± 3.15	6.85 ± 3.42
Cd _B	1.00 ± 1.02	0.99 ± 0.93	1.02 ± 1.16
Pb _B	55.9 ± 33.9	54.3 ± 34.6	58.8 ± 32.6
Hearing loss, dB			
HL ₅₀₀ ^b	13.3 ± 6.9	12.4 ± 5.0	14.8 ± 9.15
HL ₁₀₀₀	12.9 ± 7.2	12.0 ± 5.8	14.6 ± 8.92
HL ₂₀₀₀	12.5 ± 8.4	11.7 ± 7.5	13.8 ± 9.73
HL ₃₀₀₀	16.2 ± 13.2	14.7 ± 12.5	18.8 ± 14.2
HL ₄₀₀₀	22.2 ± 17.2	18.6 ± 15.1	28.3 ± 18.8
HL ₆₀₀₀	25.5 ± 18.1	20.8 ± 15.6	33.5 ± 19.1
HL ₈₀₀₀	19.0 ± 18.0	14.8 ± 15.3	26.3 ± 19.9

Noise_{Avg}—average noise exposure level; Noise_{Max}—maximum noise exposure level.

^a Criteria include the following: no congenital abnormality, no occupational organic solvent exposure, hearing loss difference no more than 15 dB between both ears, and subject's parents having no ear-related medical history.

^b HL₅₀₀—hearing loss level at 500 Hz, HL₁₀₀₀—hearing loss level at 1000 Hz, etc.

Of the six metals examined in the blood, the highest levels were observed for zinc (11097 ± 2090 µg/L) and copper (724.6 ± 105.4 µg/L), as these are both essential elements in human body. Among the toxic elements, lead was most commonly found (55.9 ± 33.9 µg/L) and cadmium was least commonly found (1.00 ± 1.02 µg/L) (Table 1). There were no statistically significant differences between metal levels among individuals included and not included groups, except for copper ($p = 0.05$).

The greatest magnitudes of hearing loss were observed for the frequencies of ,000 Hz and 4000 Hz, (25.5 ± 18.1 and 22.2 ± 17.2 dB, respectively), followed by those of 8000 Hz and 3000 Hz. Similar trends of hearing loss by sound frequency were observed for both the included and not included groups. However, compared with the included group, the non-included group was consistently with greater hearing losses across different sound frequencies, with the highest difference observed for 4000, 6000, and 8000 Hz. This phenomenon might be ascribed to the fact that all 153 subjects of the non-included group were categorized into this group because of not meeting the inclusion criteria of hearing loss between both ears of no more than 15 dB. With hearing loss difference at this level or over, these non-included subjects might subject to relatively serious hearing loss, and therefore presented a higher level of hearing loss as compared with the included group. Meanwhile, for those 259 subjects in the included group, there was no significant difference in hearing loss between the left and right ears for each sound frequency (paired t -test).

The distribution of study subjects with hearing loss are presented in Fig. 1 by sound frequency with different hearing loss thresholds. The sound frequency of 6000 Hz had the highest percentage of hearing loss for all tested thresholds except that of 30 dB, followed by sound frequencies of 4000, 8000, and 3000 Hz. Additionally, in contrast to the decreasing trend of hearing loss percentage for the low sound frequencies given the hearing loss threshold was set at high as 20, 25, or 30 dB, increasing percentages of subjects with

Fig. 1. Percentage distribution of subjects with hearing loss by sound frequency and hearing loss threshold ($n = 259$).

hearing loss were observed for low sound frequencies of 500, 1000 Hz when the hearing loss thresholds were set as 5, 10, and 15 dB.

Noise levels around the steel plant, by working zones, are presented in Table 2. The highest average noise level was observed at the electric arc furnace area (85.5 ± 8.6 dB), followed by the rolling, mineral stock, utility, and slab continuous caster, with averages around 80 dB. The lowest noise level was found in the office zone (62.2 ± 0.5 dB). The noise levels in the control rooms of certain working zones were also measured, of which the levels were generally less than those of the corresponding zones by 4 to 15 dB. The airborne concentrations of 6 metals in total particulate were relatively high at the electric arc furnace, mineral stock, and converter compared with other zones. The highest levels of zinc, cadmium, and lead were observed in the electric arc furnace area, whilst those of manganese and copper were in the converter area and that of arsenic was in the mineral stock area.

Table 3 shows the correlation matrix of the blood metal levels and sound frequency-specific hearing loss levels of the study subjects. Blood lead level was correlated with blood cadmium ($p < 0.005$), copper ($p < 0.05$), manganese ($p < 0.05$) and arsenic levels ($p < 0.05$). In addition, blood lead level was also found to be correlated with levels of hearing loss, with this association small in magnitude for the low frequencies ($p < 0.05$) but high in magnitude for the high frequencies ($p < 0.0005$). All of the sound frequency-specific hearing loss levels were highly correlated with each other ($p < 0.0005$).

Fig. 2 presents the levels of average hearing loss stratified by blood lead levels and sound frequencies. No difference in hearing loss was observed between the low (≤ 4 µg/dL) and medium (4–7 µg/dL) blood lead groups except for that of 4000 Hz. However, for the high blood lead group (≥ 7 µg/dL), there were significant increased levels of hearing loss for all tested sound frequencies except 1000 Hz, with the most significant elevation observed for 6000 and 4000 Hz ($p < 0.0005$), followed by 8000 and 3000 Hz ($p < 0.005$). Mild increased levels of hearing loss were also observed for the medium blood lead group for all tested sound frequencies ($p < 0.005$ to $p < 0.05$), except for 1000 and 2000 Hz. Fig. 3 further presents the distributions of hearing loss by noise exposure levels and blood lead levels. Those in the high blood lead groups (≥ 7 µg/dL) with high level of noise exposure (≥ 85 dB) experienced greater hearing loss at sound frequencies of 3000, 4000 and 6000 Hz ($p < 0.05$). Similar elevation was also found for the high blood lead groups with medium level of noise exposure (80–85 dB) at sound frequencies of 4000 and 6000 Hz ($p < 0.05$). Even among those experienced the lowest noise level (≤ 80 dB), there was a trend of increased blood lead associated with elevated hearing loss, though failed to reach statistical significance

Table 2

Measurements of levels of airborne metal and noise stratified by working zones.

	Working zones							
	Mineral stock	Electric arc furnace	Converter	Vacuum oxygen decarburization	Slab continuous caster	Rolling	Utility	Office
Noise levels, dB								
Sample size	5	7	2	2	6	3	6	3
Noise_ave	81.1 ± 6.4	85.5 ± 8.6	77.6 ± 10.0	75.7 ± 5.4	79.9 ± 6.4	81.3 ± 1.8	80.8 ± 4.3	62.2 ± 0.5
Noise_max	92.5 ± 13.1	95.8 ± 10.7	88.8 ± 16.2	85.7 ± 9.9	88.2 ± 6.8	92.3 ± 3.1	93.3 ± 7.1	71.2 ± 1.3
Control rooms						*	–	–
Noise_ave	70.4 ± .	70.9 ± .	70.5 ± .	71.8 ± .	73.4 ± .	–	–	–
Noise_max	73.5 ± .	80.0 ± .	77.3 ± .	78.7 ± .	83.3 ± .	–	–	–
Airborne metal levels, µg/m ³								
Sample size	5	3	6	5	3	3	–	–
Mn	40.3 ± 40.3	21.0 ± 24.4	47.3 ± 76.5	17.5 ± 18.2	3.6 ± 4.8	4.25 ± 1.97	–	–
Cu	5.64 ± 6.20	5.67 ± 7.78	8.64 ± 11.00	2.45 ± 1.75	1.52 ± 1.11	1.02 ± 1.10	–	–
Zn	10.1 ± 8.0	479.6 ± 506.8	45.5 ± 76.1	4.5 ± 3.9	0.91 ± 0.43	31.4 ± 28.9	–	–
As	0.53 ± 0.99	0.13 ± 0.14	0.26 ± 0.40	0.02 ± 0.01	0.02 ± 0.01	0.12 ± 0.05	–	–
Cd	0.07 ± 0.08	0.45 ± 0.72	0.11 ± 0.12	0.01 ± 0.01	0.01 ± 0.01	0.04 ± 0.04	–	–
Pb	3.63 ± 2.33	23.4 ± 35.0	18.2 ± 20.0	1.51 ± 1.25	0.59 ± 0.23	4.10 ± 4.63	–	–

*No data.

**No standard deviation calculated since only one measurement value in this category.

probably because of the small number of individuals in these categories.

Logistic regression model analyses indicate that, after adjusting for the age effect and noise exposure level, high level lead in blood (≥ 7 µg/dL) is associated with hearing loss at the sound frequencies of 3000, 4000, 6000 and 8000 Hz ($p < 0.005$ to $p < 0.05$). The odds ratios are largest for the frequencies of 4000 Hz, 6.26, and of 8000 Hz, 6.16. Meanwhile, there was a subtle association for medium level of blood lead (4–7 µg/dL) with hearing loss level at the frequencies of 4000 Hz, but not statistically significant. Also, there was no interaction between blood lead level and noise exposure level on hearing loss level. And, no effect on hearing loss was observed for gender, cigarette smoking and use of ear protection, either.

4. Discussion

Unlike prior research that has found an association between a relatively high blood lead level (30 to 50 µg/dL) with hearing loss or neuro-ototoxicity (Counter and Buchanan, 2002; Forst et al., 1997; Wu et al., 2000; Bleeker et al., 2003), the present study found that a blood lead level greater than 7 µg/dL is related to hearing loss (Fig. 2). In fact, the work place that had the highest percentage of workers with hearing loss was the electric arc furnace area, in which the workers' average blood lead level was around 9 µg/dL. Although epidemiological studies

consistently showed that lead can be neurotoxic to children at concentrations below 10 µg/dL (Rabinowitz et al., 1992; WHO, 2007; ATSDR, 2007), there was no report on the hearing impairment under such a low level, as traditionally occupational health professionals considered 30 µg/dL as the permissible exposure limit (ACGIH, 2008). Nonetheless, all the other 5 metals measured in workers' blood did not show a consistent correlation with different frequencies of hearing loss, as demonstrated in Table 3. And the logistic regression analysis, after adjustment with age and noise level, showed a consistent association between mild elevation of blood lead and hearing impairment between 3000 and 8000 Hz (Table 4). Even if the hearing loss criterion was set at 20 dB instead of 25 dB, the logistic regression analysis still showed the same association across different sound frequencies with significant odds ratio (data not shown). However, if the criterion was set at 15 dB, no significant odds ratio was found though the trends of odds ratio at different sound frequencies seemed still similar. Fig. 3 further indicates that, at the frequencies of 3000–8000 Hz, there seems a consistent trend of significantly increasing hearing loss for blood lead levels above 4–7 µg/dL under the noise level above 85 dB. In addition, blood lead levels above 7 µg/dL appeared to enhance the oto-toxicity of noise at a lower level of 80–85 dB for 4000 Hz and 6000 Hz. These findings indicated that the association between increased blood lead levels and hearing loss observed in this study was not confounded by the noise exposure level. Thus, the association found in the present study may imply that

Table 3Correlation matrix of the subjects' blood metal levels, hearing loss levels, and noise exposure levels.^a ($n = 259$).

	Mn_B	Cu_B	As_B	Zn_B	Cd_B	Pb_B	HL ₅₀₀	HL ₁₀₀₀	HL ₂₀₀₀	HL ₃₀₀₀	HL ₄₀₀₀	HL ₆₀₀₀	HL ₈₀₀₀	Noise _{Avg}	Noise _{Max}
Mn_B		0.20**	0.06	0.01	0.05	0.12*	0.02	0.00	−0.02	−0.01	−0.01	−0.04	−0.02	0.10	0.08
Cu_B			0.09	0.04	0.05	0.14*	−0.01	−0.01	0.02	0.03	−0.01	0.06	0.01	0.10	0.06
As_B				0.01	0.01	0.13*	0.05	−0.00	−0.01	−0.02	−0.04	−0.05	−0.07	0.07	−0.00
Zn_B					0.05	0.02	0.08	0.12	0.06	0.03	−0.00	0.03	0.04	0.03	0.05
Cd_B						0.20**	0.14*	0.15*	0.08	0.05	0.07	0.04	0.03	−0.04	−0.06
Pb_B							0.13*	0.11	0.19**	0.21***	0.24***	0.23***	0.22***	0.36***	0.30***
HL ₅₀₀								0.67***	0.53***	0.36***	0.26***	0.24***	0.29***	0.12	0.06
HL ₁₀₀₀									0.72***	0.41***	0.31***	0.33***	0.36***	0.08	0.02
HL ₂₀₀₀										0.63***	0.47***	0.51***	0.51***	0.16*	0.08
HL ₃₀₀₀											0.85***	0.74***	0.70***	0.22***	0.14*
HL ₄₀₀₀												0.82***	0.71***	0.21***	0.12*
HL ₆₀₀₀													0.85***	0.22***	0.15*
HL ₈₀₀₀														0.19**	0.12
Noise _{Avg}															0.90***

^aHL₅₀₀—hearing loss level at 500 Hz, HL₁₀₀₀—hearing loss level at 1000 Hz, etc. Noise_{Avg}—average noise exposure level; Noise_{Max}—maximum noise exposure level.^b* $p < 0.05$, ** $p < 0.005$, *** $p < 0.0005$.

Fig. 2. Average hearing loss by sound frequency and blood lead level.

the level of lead exposure leading to hearing loss or neuro-ototoxicity may be less than previously reported, or, that there may be no threshold of lead exposure for hearing loss (WHO, 2007).

This study showed that the highest percentage of study subjects with hearing loss, as well as the highest level of hearing loss, was identified at the sound frequency of 6000 Hz, followed by 4000 Hz, 8000 Hz, and 3000 Hz. This is slightly different from the typical sign of hearing loss from noise exposure, which is characterized with a “notching” of the audiogram at 4000 Hz, that, however, depends on multiple factors, including the frequency of the damaging noise and the sound resonance of the ear (McBride and Williams, 2001). For instance, the U.S. OSHA adopts a 10-dB confirmed threshold shift from baseline in pure tone average at 2000, 3000, and 4000 Hz as an important early indicator of permanent hearing loss (Rabinowitz et al., 2003). The findings in the present study indicate that the effect of lead exposure on the hearing loss of high sound frequencies is more significant than that of the low sound frequencies. The findings also imply that the mechanism of ototoxic insult resulting from lead exposure might not necessarily be the same as that of pure noise exposure, which corroborates with a previous report (Counter and Buchanan, 2002), although the author only studied one frequency (i.e., 4000 Hz).

Occupational noise exposure is thought to be the major cause for high-frequency hearing loss among workers. However, an enhancement of the auditory impairment, due to the combination of increased lead absorption and noise exposure in the workplace, has been indicated in prior research (Schwartz and Otto, 1991; Forst et al., 1997), especially for long term exposure (Wu et al., 2000). The association of low blood lead level with hearing loss in the present study might be possibly explained by the lead-induced neuro-ototoxicity on cochlea and retrocochlea (Holdstein et al., 1986; Schwartz and Otto, 1991; Otto and Fox, 1993; Farahat et al., 1997). For instance, lead exposure might impair conduction in the auditory nerve and the auditory pathways in the lower brainstem (Bleecker et al., 2003). Meanwhile, the outer hair cell is more vulnerable than the inner hair cell. When the outer hair cell is affected by the increased blood lead, it might lose the protective damping effect for the inner hair cell (Mountain, 1980). In other words, the inner hair cell may become more easily damaged, because it is exposed to the less attenuated sound levels.

As one of the major factors for ototoxicity, noise exposure was also examined in the present study. The risk of noise-induced hearing loss increases significantly with chronic exposure above 85 dB for an 8-h time-weighted average (ACOEM, 2003). This is particularly true for continuous exposure. The results of the present study indicated that noise exposure and hearing loss were correlated, but that the association was moderate. For instance, in the multivariate analyses, average noise level and blood lead levels were both included as predictors of hearing loss in the logistic regression model analysis.

However, only blood lead level was moderately associated with hearing loss for certain sound frequencies around the whole spectrum (Table 4). The association between noise exposure and hearing loss in this study might be a result of the special pattern of noise exposure during the on-site manufacturing process in this study. The time-weighted average noise levels of the working sites in this study plant varied between 75 and 85 dB (Table 2), with the highest average noise level found at the electric arc furnace area (85.5 ± 8.6 dB). These noise levels were lower than or just around the action level of 85 dB for adopting hearing loss protection measure, and also well lower than the occupational permissible exposure limit of 90 dB (ACGIH, 2008). Additionally, these workers might be exposed to high noise levels only intermittently because, according to the manufacturing process, they only spend about one-third of their working hours in these high noise areas. For the rest of the working hours, these workers mostly stayed in the control rooms for other work tasks, where the background average noise levels were between 70 and 74 dB (Table 2).

From the viewpoint of industrial hygiene, the occupational hazard exposures at the work place that result in elevated blood lead levels are of concern. Findings from the present study indicated that, although there were six metals monitored in airborne samples, only airborne lead level was found to be significantly correlated with the corresponding blood lead level in the working sites (data not presented). In addition, the highest total airborne lead levels were observed at the electric arc furnace and converter areas ($23.4 \pm 35.0 \mu\text{g}/\text{m}^3$ and $18.2 \pm 20.0 \mu\text{g}/\text{m}^3$, respectively) (Table 2). This was very similar to the distributions of blood lead level and hearing loss of the workers among the different working zones. This directly supports the fact that the elevation of lead in the blood of these steel workers could be attributed to the lead exposure at their working areas. It also implies that an appropriate measure should be adopted to reduce the relatively high level of airborne lead exposure.

Of course, some limitations of this study exist. Occupationally induced hearing loss, in contrast to acoustic trauma, develops slowly over a long period of time (usually several years) as the result of exposure to continuous or intermittent loud noise. Therefore, cumulative environmental exposure measurement would better represent the workers' exposure to loud noise for the most accurate depiction of the exposure-response relationship. However, the present study only used the worker's employment history and a one-time measurement of noise exposure. Nevertheless, the steel industry has a constant manufacturing process, so it is fair to assume that workers are steadily exposed to hazards associated with their working conditions. Therefore, using a cross-sectional measurement of noise levels and age or the number of years spent at the plant and may be a good alternative indicator of noise and lead exposure throughout the past years.

On the other hand, although low blood lead level was recognized as a potential culprit for noise-induced hearing loss at all sound frequencies, with limited sample size, the statistical power may not be large enough to verify the relationships between the exposure to noise or blood lead and the hearing loss. Thus, certain obvious dose-response trends could not be ascertained when the statistical examination was performed for each combination of noise and blood lead levels (Table 4 and Fig. 3). Future research should recruit a large cohort of employees and track this cohort over time for accumulated exposure estimates in order to further explore the effect of lead exposure on the noise-induced hearing loss. Future research should also consider additional factors that may affect the risk of lead exposure such as iron and calcium deficiencies, modification effect of ALAD genotype, or having organ diseases affected by lead toxicity (Skerfving, 2005).

In conclusion, the present study finds a significant association between a relatively low level of lead in the blood (around $7 \mu\text{g}/\text{dL}$ or above) and the noise-induced hearing loss at various sound frequencies. The largest impact was found at the high sound frequencies of hearing loss, especially 6000 Hz. Lead exposure may contribute to hearing loss via impairing the auditory nerve conduction and/or the protective

Fig. 3. Hearing loss levels by blood lead level, noise level, and sound frequency.

Table 4
Effect of blood lead and noise level on the odds ratio for hearing loss by frequency after adjusting for age and average noise level or blood lead level ($n = 259$).

Variable	HL ₅₀₀			HL ₁₀₀₀			HL ₂₀₀₀			HL ₃₀₀₀			HL ₄₀₀₀			HL ₆₀₀₀			HL ₈₀₀₀		
	Hearing loss, dB	OR (95% CI)		Hearing loss, dB	OR (95% CI)		Hearing loss, dB	OR (95% CI)		Hearing loss, dB	OR (95% CI)		Hearing loss, dB	OR (95% CI)		Hearing loss, dB	OR (95% CI)		Hearing loss, dB	OR (95% CI)	
	≤25	>25		≤25	>25		≤25	>25		≤25	>25		≤25	>25		≤25	>25		≤25	>25	
Blood lead	≤4 µg/dL	96	0	96	0	1.0	96	0	1.0	92	4	1.0	89	7	1.0	85	11	1.0	93	3	1.0
	4–7 µg/dL	104	1	103	2	NA	105	0	0.75	101	4	0.75	82	23	3.54	82	23	2.11	95	10	3.0
	≥7 µg/dL	58	0	56	2	NA	51	7	4.49**	44	14	4.49**	35	23	6.26**	37	21	3.06*	45	13	6.16*
Noise level	≤80 dB	54	0	54	0	1.0	53	1	1.0	51	3	1.0	45	9	1.0	47	7	1.0	48	6	1.0
	>80 dB	204	1	201	4	NA	199	6	0.50	186	19	0.75	161	44	0.89	157	48	1.46	185	20	0.48
									(0.04–5.75)						(0.37–2.13)			(0.58–3.63)			(0.16–1.41)

* $p < 0.05$, ** $p < 0.005$

NA – not appropriate for statistical calculation due to a number of zero in one cell of the contingency table.

function of the outer hair cell, which, in turn, directly expose the inner hair cell to the less attenuated sound levels. Future research should consider both a large sample size and a longitudinal design to further explore the mechanisms through which low levels of lead in the blood are associated with noise-induced hearing loss.

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